1. Introduction

As rolling bearing applications diversify and the equipment in which rolling bearings are used becomes increasingly high-performance and functionally advanced, great changes are being brought about in rolling bearing usage environments. Customers are demanding that rolling bearings perform at high speeds, at low and high temperatures, under high loads, and in various special environments while having such features as being lightweight and compact, low torque, noise levels, and long life.

In order to develop bearings that meet these requirements, great advances will first have to be made in such areas as basic theory and analysis; metallic materials and heat treatment; lubrication; basic element technology; new materials (resins and ceramics); and surface treatment technology.

This paper looks at trends in each of these technical fields and presents outlooks for the future.

2. Theoretical Analysis

Remarkable progress has been made over the past 10 or 20 years in the bearing technology. Many excellent analysis programs and techniques have been developed, and optimal design is now carried out through simulation and technical researches utilizing these. Figure 1 shows analysis technology required for the design of bearings and examples of analysis projects carried out by Koyo. The basic theory (Hertz theory) required for static analysis was established at the end of the 19th century, but the kind of analysis required in order to discuss dynamic performance has only become possible in relatively recent years. Progress in the field of computers and the simultaneous establishment of elastohydrodynamic lubrication theory (hereinafter referred to as "EHL") have largely been the driving force behind this. In other words, expanded application of EHL to bearings and EHL numerical analysis technology have enabled great progress.

By solving the contact problems, including hydrodynamic theory, EHL has enabled the detailed film thickness distribution and pressure distribution of the contact area to be known. Life can be determined from the ratio of oil film thickness to surface roughness and torque from the pressure distribution, and performance characteristics such as traction and heat generation under sliding conditions can be determined. In 1987, Koyo developed a device for measuring oil film thickness that makes use of a light interference method and succeeded in clarifying oil film behavior regarding various types of oils under various operating conditions. Koyo also conducted theoretical investigations and with a 3D model was able to obtain pressure distribution at high pressures exceeding 4 GPa, where it is difficult to obtain convergence by normal analysis. Also, using a 2D model, a dynamic friction torque theoretical equation was also established for roller bearings that matches actual measurement values well.

In the latter half of the 1980s, EHL and the traction model were devised for dynamic analysis, and it became possible to calculate the heat generated by rolling element spinning, sliding, etc. and to analyze rotational sliding, retainer behavior, etc. Koyo established a technique for the real-time simulation of the roller bearing system and implemented it in a production model. In step with recent technical improvements in the equipment of numerous industries, rolling bearings are required to be usable at high speeds, at high and low temperatures, under high loads and in special environments while having increasingly high performance in the areas of life, noise, torque, etc. Herein these trends are reviewed, and brief comments are made about the outlook for R&D in rolling bearing basic technology and element technology.

Key Words: rolling bearing, performance, trend, analysis, material, grease, retainer, ceramic
of non-repetitive run-out (NRRO), an important characteristic of ball bearings for HDD spindles. HDD bearings are required to display nano-order performance, and using the said technique, Koyo can determine the factors of greatest of influence and use this information to raise its machining precision.

Dynamic analysis is an effective tool for predicting the dynamic performance of bearings, but there are problems related to experimental verification and convergence. How to improve reliability and calculation technology is the theme for future study.

This analysis is currently being applied to a wide range of fields, including strength of materials, dynamics of machinery, kinetics, vibration, heat, EHL, fatigue and lubrication. In the future, analysis will become more advanced, and faster, and the analytical field will be expanded. Until now this analysis has been applied mostly to individual bearings, but in the future we aim to apply this to unit products comprising the bearing and peripheral parts.

3. Materials and Heat Treatment

3.1 Material Technology Development

Efforts to develop material technology for rolling bearings are illustrated in Fig. 2. Technology for extending life and that for analyzing life mechanism are the primary themes for rolling bearing material technology development. In recent years, the development focus has shifted toward the meeting of customer demands for lower costs. Examples of Koyo efforts to develop technology to extend bearing life are shown in this figure. Specific content is reported in detail other articles herein, so only a brief description shall be provided here.

- Original materials (contaminant/corrosion/high temperature resistant)
- High-refined (improvement of standard materials)
- Heat treatment/machining/surface treatment
- Life calculation formula
- Remaining life

Fig. 2 Material technology

3.2 Technology for Extending Life

Measures to extend bearing life include 1) measures to improve life in clean lubricants, 2) measures to improve life in contaminated lubricants, and 3) measures to improve life in high-temperature environments.

3.2.1 Improving Life in Clean Lubricants

Measures to improve rolling fatigue life in clean lubricants concern suppressing the generation and progression of material cracking. This requires improvement of material cleanliness (reduction of nonmetal inclusions) and improvement of the strength of the material itself. The former was achieved through the development and commercialization of the high-refined bearing steel HRS and the latter through the high-strength bearing steel GT.

3.2.2 Improving Life in Contaminated Lubricants

Bearings for automobile transmissions and differentials must operate in lubricants containing contaminants such as gear wear-particles, making it easy for flaking originating in impressions to occur. Bearing surface hardness must be improved in order to extend life in contaminated lubricants, and increasing the wear resistance of rolling surfaces and otherwise making it difficult for impressions to be made are effective. In this regard, Koyo developed SH bearings and KE bearings by developing a new surface hardening heat-treatment method. Currently SH bearings are used normally as deep-groove ball bearings and KE bearings as tapered roller bearings.

3.2.3 Development of Bearing Steel for Semi-High Temperatures

In order for bearings to be used in the semi-high-temperature range of 100°C to 200°C, the improvement of temper softening-resistance, the suppression of metallographic structural changes caused by repeated fatigue, and the suppression of hardness reduction are necessary. To meet these requirements, Koyo has developed the semi-high-temperature bearing steel KUJ7.

Regarding the extension of rolling bearing life, there are opposing factors affecting life that are difficult to solve simultaneously with conventional technology, such as hardness and toughness. But heat treatment with the primary purpose of surface hardening is an effective means of coping with such problems.

Demands for the use of cheaper materials will continue to grow. Progress in recent years in computer technology has enabled the complex control of multiple heat treatment conditions, such as atmosphere, temperature and time. Progress has also been made in the area of furnace gas flow analysis. The fusing of these technologies in order to develop heat treatment technology enabling the characteristics necessary for long bearing life to be met without the use of expensive materials will be a subject of continued study in the future.
4. Lubrication Technology

Lubrication technology plays a vital role in the performance of rolling bearings and is therefore an important element technology. Eighty percent of rolling bearings use grease lubrication. Grease lubrication has numerous advantages over oil lubrication, including the following: Grease-packed bearings do not require a sealed structure; they are more compact and lightweight, and they are easier to maintain. As advances have been made in the performance and reliability of mechanical equipment, the usage conditions of rolling bearings have become severer, which in turn has brought about a demand for greases with improved performance and longer life. Urea grease, with performance superior to that of conventional Na or Li-based greases, was commercialized in the United States during the 1960s, and Koyo as well was able to develop the urea grease KNG series. Koyo developed and used Greases not only with long life and for use in high-temperature, high-speed and high-load environments but also with low torque, low noise, low particle generation and high rust resistance. And today, basic research is being conducted to develop greases to meet increasing requirements for safety and environmental protection. The main areas of effort are indicated in Fig. 3.

Examples of greases developed for main applications are given in the following sections.

Fig. 3 Lubrication technology

4.1 Grease for Alternator Bearings

Urea/PAO grease (KNG170), developed to be suitable for high temperatures and speeds, can be used in temperatures up to 150°C. Also, a urea/ADE/organometallic grease for extreme pressures was developed to prevent the early flaking that can be caused by the high strain and vibration levels of polyvinyl V-belts. This grease has improved bearing reliability and can be used in temperatures up to 170°C.

4.2 Grease for Bullet Train Bearings

Although oil lubrication had conventionally been used for bullet trains, in 1997 Koyo developed a urea grease for high-speed, long-life applications that possessed superior heat resistance and oxidation stability as a grease lubricant for JR’s new 500-series Nozomi bullet trains.

4.3 Grease for Electrical and Information Apparatuses

Although lithium and ester greases have traditionally been used for small motors, Koyo developed a long-life, low-noise urea grease (KNG144) for these applications.

4.4 Environmentally Friendly Lubricants

In 1998 Koyo developed and commercialized a vegetable-oil-based biodegradable grease (BioSuper LL Grease) that is made from calcium soap and rapeseed oil and possesses long life. This grease was awarded Japan’s “Eco Mark” certification. Other products aimed at preventing environmental pollution include Solpack bearings, which were developed in 1996 and are packed with a solid lubricant.

As technical innovation progresses and demands for rolling bearings with improved performance and functions increase, R&D for the purpose of creating economical, high-performance lubricants that meet environmental and safety requirements will become increasingly important in the future. Koyo will aim to develop lubrication technology through basic research in the areas of bearing lubricant behavior, lubricant mechanisms, lubricant life, lubricant and friction-surface tribo-chemical reactions, etc.

5. Resin Materials

The mechanical properties and heat resistance of resin materials are generally poor in comparison with those of metal materials, but the feature characteristics of resin can be efficiently realized in wide usage environments. In particular, the flexibility, self-lubricating capability, lightness (advantageous for high-impact and high-vibration environments), corrosion resistance and ability to be shaped freely make resin a suitable material for bearing retainers.

Examples of current efforts are shown in Fig. 4.

Fig. 4 Resin technology

Resin materials shifted from polyacetal resins to polyamide resins as bearing usage environments became severer and in particular as requirements for heat resistance and oil resistance increased, but because of the need to balance cost and performance, the material used most commonly today is glass-fiber-reinforced polyamide resin.
However, when usage temperature exceeds 180°C, or impact resistance requirement or other usage conditions are especially severe super-engineering plastic PEEK resin, which excels in heat resistance, is sometimes used.

Koyo is standardizing resin retainer materials used for each bearing type and application classification. Regarding the direction of future research, molding technology and design optimization will become increasingly important, along with the development of new materials.

### 6. Ceramic Materials

Engineering ceramics, the most representative of which are silicon nitride (Si₃N₄) and silicon carbide (SiC), possess superior heat resistance, corrosion resistance and wear resistance and have long been used in key elements of engine parts, electronics products and semiconductor components. However, there were few examples of ceramic being used for the main structures of parts. However, in 1980 Koyo began working to use ceramic as a rolling bearing material and succeeded in developing a silicon nitride material that possessed the necessary characteristics. In 1985, we commercialized a ceramic ball bearing made of silicon nitride material, and bearings of this type are now used for numerous applications. A brief introduction of each application is provided below.

#### 6.1 Ceramic Bearings for Special Environments

The features of silicon-nitride ceramic bearings make them usable in special environments where metal bearings cannot be used, such as in high-temperature environments, corrosive environments, magnetic environments, and vacuum environments. Applications include semiconductor manufacturing equipment, equipment for nuclear power plants, and equipment for use in space. A series of products for each application has been prepared.

#### 6.2 Ceramic Bearings for Machine Tools

Ceramic bearings are highly suitable for applications requiring high-speed operation, high rigidity, and minimal temperature rise. Specifically, ceramic is suitable because it possesses the following characteristics:

1. It has low density and is able to lower contact stress through the reduction of centrifugal force during high-speed rotation.
2. Its high rigidity raises bearing and main shaft rigidity.
3. It enables bearings to have little heat generation and not to suffer the contact-area damage normally associated with insufficient lubrication.

#### 6.3 Ceramic Bearings for Vehicles

A typical example of ceramic bearings for high-temperature and high-speed applications is ceramic ball bearings for turbochargers. Bearing temperatures during turbocharger operation range from 200°C to 300°C, and the dn value for rotational speed reaches 1.3 million. Lubrication is by oil jet, and the bearing requires a comparatively large quantity of oil; however, sludge and other contaminants in the oil can attack bearing surfaces and cause damage. The following characteristics of ceramic balls make them suitable for such applications: 1) heat resistance (use of semi-high-temperature material developed by Koyo for raceways), 2) low density, and 3) hardness. In particular, ball damage caused by contaminants can be minimized through the use of ceramic balls.

#### 6.4 Ceramic Bearings for Electrical Equipment

Ceramic ball bearings for HDD spindles and polygon mirror scanner motors have been developed and are being mass-produced. Both of these applications require bearings with 1) low torque, 2) low particle generation, and 3) long life; in particular, these bearings must have superior performance in the areas of vibration, torque and NRRO. Damage to the ceramic balls and metal raceways caused by long-term operation with insufficient lubrication is minimized because of the superior tribological characteristics of ceramic under insufficient lubricating conditions and also by proper lubricant selection and the optimizing of lubricant quantity and application conditions.

As described, ceramic bearings have come to be used in a wide variety of applications, but development of new high-performance ceramic materials and bearings for new applications will continue.

Ceramic bearing costs have been lowered over the past several years by increasing quantities (benefit of lot production) and by improvements in such areas as materials, manufacturing technology, and quality assurance technology. Koyo will continue working to develop ceramic bearings with further improved performance, cost and quality. Concerning our basic research as well, we wish to improve the quality and quantity of our existing data base in order to enhance our ability to provide products with high reliability.

#### 7. Surface Treatment Technology

Rolling bearing surface treatment technology provides bearings with added value and enhances their performance. Since the 1970s Koyo has been developing surface treatments of various types as well as bearings and other products making use of such technology.

*Figure 5* shows surface treatment technologies and the products to which they are applied.

Surface treatment technologies are roughly divided into those whereby the surface is hardened by nitriding or carburizing and those whereby the surface is coated with a soft metal or high polymer film. Representative products using the latter type that have been developed are introduced here.

#### 7.1 Silver-Ion-Plated (Ag-IP) Bearings for Vacuums

In 1978, Koyo succeeded in marketing the world’s first silver-ion-plated (Ag-IP) bearing for vacuum, which features stainless steel balls plated with silver. Because fluid lubricants such as conventional oils and greases cannot be used in vacuum environments, the use of these bearings, which use...
8. Conclusion

In this paper, recent results and described that Koyo has achieved regarding basic and element technology related to bearings as well as the direction of R&D in the near future. Rolling bearings have few elements and an extremely simple structure. In order to continue advancing the development of these fundamental parts, it will be necessary to carry out research at the substance and molecular levels in such areas as new materials, heat treatments, surface improvements, and their process methods.

Although this paper has concerned individual bearings, the optimal designing of mechanical systems incorporating bearings will also be an important topic of research. Koyo will continue R&D regarding not only bearings but also peripheral technology in order to provide society with bearings systems that place little load on the environment.

silver as a solid lubricant, has expanded significantly in step with the growth of the vacuum equipment industry.

Special applications include rotational anode X-ray tubes in the field of medicine. The severe conditions in which these bearings are used include high vacuums (up to $10^{-5}$ Pa), high temperatures (up to 550°C), and high loads (up to 2.5 GPa), and therefore in many cases full type ball bearings with heat-resistant steel balls with a special silver-ion or lead-ion plating are widely used.

7. 2 PTFE Bearings and Clean Pro\(^3\) Bearings

The rapid growth in the semiconductor, information apparatus and electronic parts industries beginning in the late 1980s and continuing through today has brought about a dramatic change in bearing requirements, with demands increasing for bearings able to be used in clean environments and corrosive environments. In response, Koyo has developed and marketed PTFE-coated bearings and Clean Pro\(^1\) bearings, which are coated with a special fluorine-based high polymer, for use in clean environments. The individual parts or the entire bearing is coated with a special fluorine-based high polymer with extremely low particle generation by a special baking method or special dipping method. The bearings are widely used as clean bearings in semiconductor and liquid crystal manufacturing equipment such as spattering equipment and CVD equipment.

Various types of surface treatment technologies, such as PVD and CVD, have been developed in recent years, and Koyo will aim to expand the application thereof in order to satisfy requirements for bearings able to be used in increasingly diversified and severe environments.

In relation to these surface treatment technologies, thin-film stress analysis and evaluation technology will be indispensable in the future, and technology concerning the materials to be plated and that related to machining after plating will need to be studied. In other words, it will be important to consider surface engineering in its entirety as a separate field of study.