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Contents

Bearings for Aircraft Gas Turbine Engines (part 2)

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1. Introduction

In recent years, new airline companies have emerged as a result of deregulation and increased demand in the industry. On the other hand, alliances between airlines have enhanced aircraft operating efficiency and consumer convenience. An important trend resulting from the more widespread use of aircraft transportation and the drive to improve operating efficiency is developing aircraft with greater long-range capability. Hence engines with higher fuel efficiency are being developed.

Twin-jet aircraft for medium and long range such as the Boeing 777 and Airbus A330 were developed to reduce operating costs. In 1998, airlines flying cross-Atlantic routes used twin-jet aircraft more than 50% of the time. A critical contribution to the success of twin-jet aircraft has been the availability of high-thrust turbofan engines with enhanced reliability.

In the development of the engine, improvement of the main shaft rolling bearing has been the key to overcoming various hurdles. Presently, important considerations for the development of bearings for aircraft engines include:

- The increased speed of the main shaft
- Increased engine thrust and the resulting need for higher bearing load capacity
- The dependable performance of bearings in extreme conditions (including oil interruption resulting from changes in the oil-level in the reservoir caused by an aircraft going into a nose-dive, and skidding, the excessive sliding of rolling elements on the raceway under high speed and low load)
- The assessment of bearing fatigue life in terms of L_1 life (99% reliable life estimation)

Day by day and application by application, requirements from engine makers become increasingly exacting and difficult for bearing manufacturers to meet. We are working to ensure the highest bearing performance and reliability by taking the following measures:

- Using high-fracture toughness and high-temperature bearing steel (i.e., M50NiL, Pyrowear675, CSS-42L, etc.) for high-speed and high-capacity bearings
- Controlling the unbalance of rolling elements (balls and rollers) in high-speed bearings
- Extending bearing life with plasma nitriding surface treatment
- Improving bearing fatigue life and resistance to sliding wear in medium-range temperatures (up to 300°C) by using carbonitriding bearing steel (SHX)

These technologies are the fruits of developmental work both on the internal properties of bearings (bearing steel, inclusions in material, microstructure, etc.) and external properties such as raceway surface-roughness and cage-guiding mechanisms. In this report, technologies that contribute to higher bearing reliability through improving bearing internal properties are presented and discussed.

2. Improvements in Bearing Internal Properties

2.1 Improvement in unbalance of balls

Balls from bearings for high-speed applications occasionally show signs of rolling and sliding contact in the form of bands of concentric circles around their exterior. In a study of three-dimensional ball motion, different traces of the projections of the north pole of magnetised balls were observed (Fig. 1).[1] The more unbalanced ball (Fig. 1a) tended to rotate more regularly around a fixed axis than the ball that was only slightly unbalanced. It therefore appears likely that the rotational axis of unbalanced balls tends to be fixed as wear progresses.

NSK measured the static and dynamic unbalance of large balls (15/8" dia.) made of M50 bearing steel for aerospace engine main-shaft bearings. We found that M50 balls have very small static unbalance, less than 0.2 µm, which reflects good geometric accuracy, but have relatively large dynamic unbalance mainly caused by the unequal

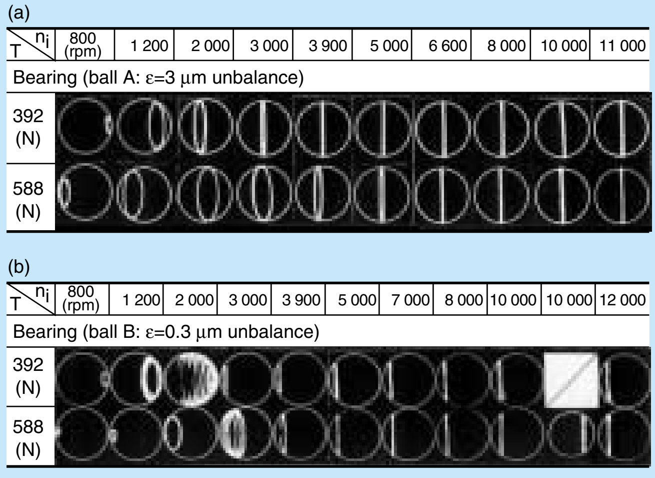


Fig. 1 Traces of ball motion with different unbalance

distribution of carbides inside them, as shown in Photo 1. Therefore, the control of ball unbalance may be needed for certain high-speed applications, particularly those using large-sized balls.

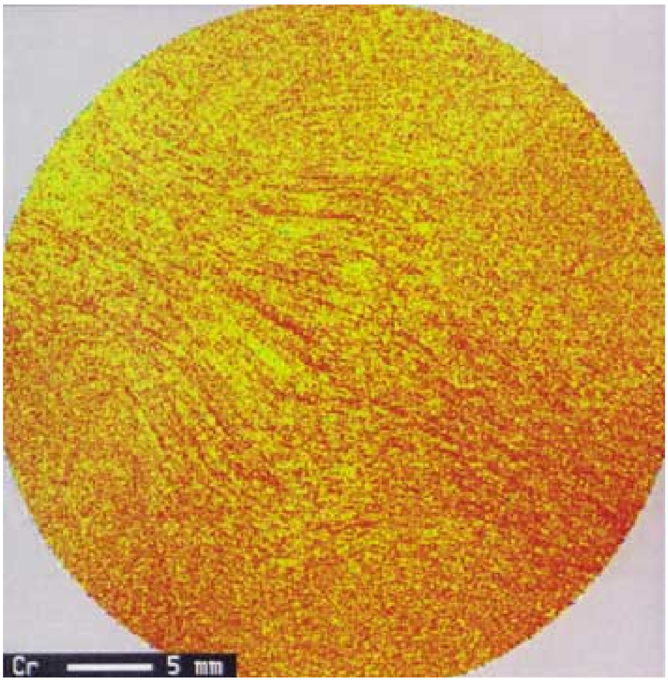


Photo 1 Distribution of Cr in M50 ball

2.2 Improvement in fracture resistance

In the high-speed application of engine main-shaft bearings, the dN value (dN = d: bearing bore diameter, mm × N: shaft speed, rpm) reaches 2.4×10^6 and the inner ring tends to break when this speed is exceeded. As countermeasures, case-hardened materials such as M50NiL and Pyrowear675 have been used because they have high compressive stress on the surface and high fracture toughness.

NSK has developed a testing method which can reproduce the fracture pattern of inner ring cracks that occur in actual bearings. For the first time, this method enables the quantitative evaluation of the relationship between hoop stress and inner ring fracture life by providing a minute half-ellipse fatigue crack (pre-crack) at a selected "origin point" on the inner ring raceway. The

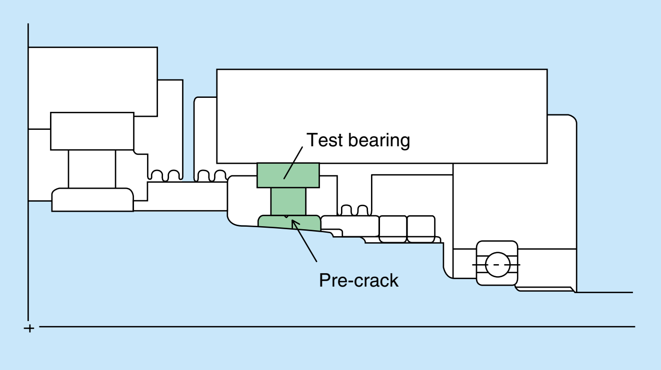


Fig. 2 Cross-section of inner ring fracture test machine

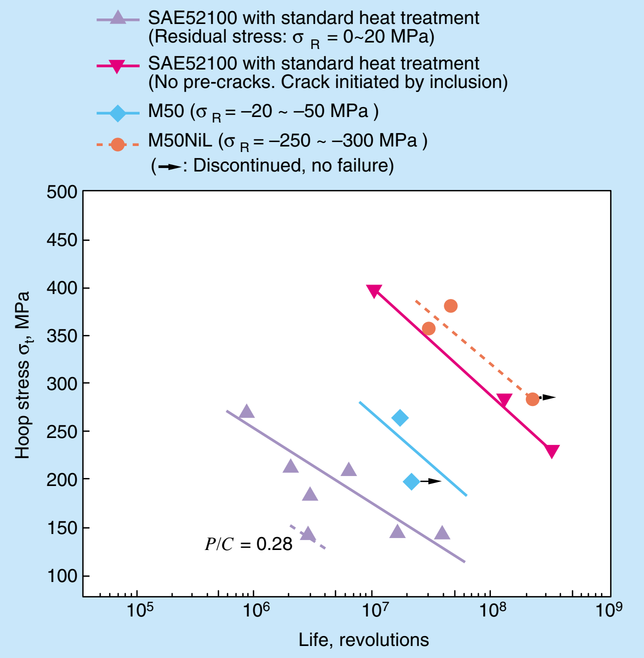


Fig. 3 Results of inner ring fracture test (P/C = 0.19)

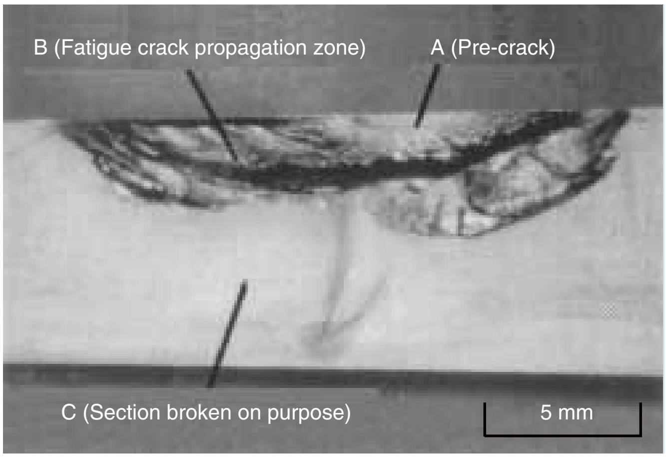
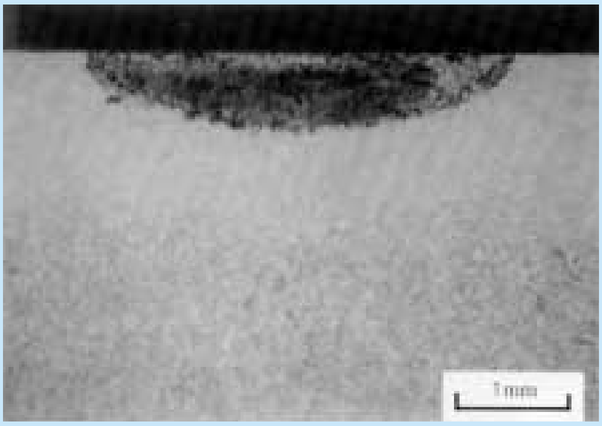


Fig. 4 Pre-crack and fatigue crack propagation (M50, Hoop stress σ_t = 200 MPa, $n = 2.2 \times 10^7$ rev.)

testing equipment is illustrated in Fig. 2. M50 and M50NiL were compared using this method and the results are shown in Fig. 3. An M50 inner ring under hoop stress of 270 MPa fractured after 1.5×10^7 revolutions and under 200 MPa hoop stress, a crack propagated but no fracture occurred after 2.2×10^7 revolutions (Fig. 4). In contrast, under higher hoop stress (280 MPa) and after far more revolutions (1.7×10^8), only slight crack propagation was observed with M50NiL steel (Fig. 5). The advantage of M50NiL in terms of fatigue crack life was thus verified quantitatively.

2.3 Improvement in rolling contact fatigue properties by surface modification

Bearing materials are required with improved rolling contact fatigue (r.c.f.) and wear resistance together with greater tolerance to poor lubrication conditions. The



Pre-crack and fatigue crack propagation zone

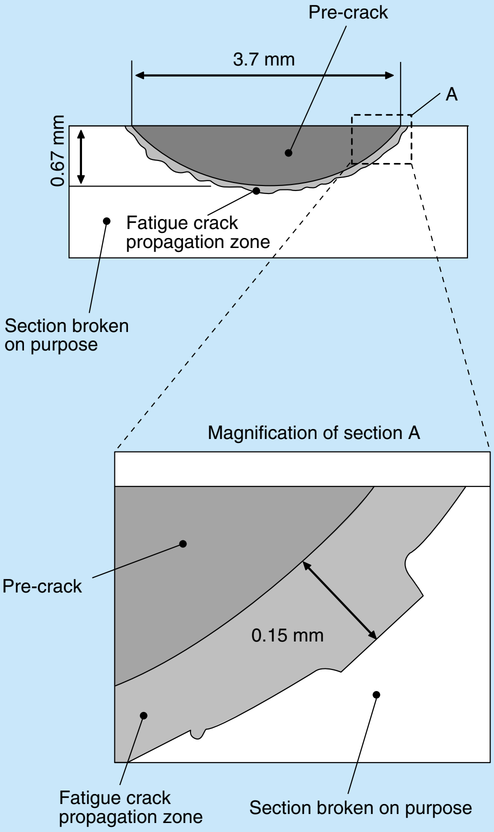


Fig. 5 Pre-crack and fatigue crack propagation (M50NiL, Hoop stress σ_t = 280 MPa, $n = 1.7 \times 10^8$ rev.)

development of new materials to meet these requirements is costly and slow due to the safety critical nature of the application. Alternatively, surface treatments, particularly thermochemical treatments such as nitriding and nitrocarburising, can be used to enhance the properties of existing bearing materials. It has been shown that nitrocarburised bearing raceways made in M50 and M50NiL materials performed better than untreated raceways in conditions of contamination, surface flaws, marginal lubrication and traction.[2] The nitrocarburising treatment, however, involves high temperatures (>500°C) and long process times (up to 32 hours) and a final grinding operation is required to remove the compound layer which performs unfavourably in r.c.f.[3]

Outlined in this section is a plasma nitriding process developed by NSK-RHP for M50 and M50NiL bearing materials. The process is performed at significantly lower temperatures and reduced process times compared to other nitriding/nitrocarburising treatments for bearing materials. Furthermore, the process conditions are such that the formation of a compound layer is prevented and distortion is maintained within acceptable levels thereby negating the need for a final grinding operation. Fatigue testing of M50 and M50NiL materials under high Hertzian contact stresses and marginal lubrication has shown that plasma nitriding significantly improves the r.c.f. resistance of both materials.

2.3.1 Materials

The plasma nitriding process was developed for M50 and M50NiL main-shaft bearing materials. The composition of M50 and M50NiL is given in Table 1 together with that of SAE52100 carbon chrome bearing steel for comparison.

M50 material is a well-established through-hardening bearing steel and is the most commonly used material for main-shaft bearings. M50NiL material, which was introduced more recently in the 1980s, is the carburising version of M50. M50NiL has similar bearing properties to M50 but higher fracture toughness in the uncarburised core.

Table 1 Composition of test materials

Material	Chemical composition (wt%)						
	C	Cr	Mn	Mo	Ni	Si	V
M50	0.8	4.1	0.3	4.3	–	0.3	1.1
M50NiL	0.1	4.1	0.3	4.3	3.4	0.2	1.2
SAE52100	1.0	1.5	0.4	–	–	0.3	–

2.3.2 Properties

To improve the r.c.f. resistance, wear/scuffing resistance and tolerance to poor lubrication conditions of M50 and M50NiL materials, a plasma nitriding process was developed that produces the following material enhancements.

(1) Surface hardness

In general the higher the surface hardness the greater the resistance to wear and debris damage. The normal surface hardness of M50 and M50NiL materials is around 750 Hv. Increasing this surface hardness by plasma nitriding would be expected to improve the wear resistance.

The surface hardness achieved by the plasma nitriding process was 975±25 Hv (Fig. 6). Although a much higher surface hardness can be achieved by plasma nitriding, a maximum of 1 000 Hv was set to limit the hardness differential between the nitrided case and the bulk material. By reducing the hardness differential the likelihood of cracking in the region of the interface between the nitrided case and the bulk material is reduced.

(2) Nitrided case depth

The plasma nitrided case depth achieved was 50±25 µm (Fig. 6) which reflects the amount of wear that can be tolerated by the bearing. Also, by adopting a relatively shallow case, the process conditions (time and temperature) can be kept to a minimum. This not only reduces cost but also the amount of distortion and the likelihood of the formation of undesirable microstructural features. Furthermore, because the specified case depth is well below the calculated depth to maximum shear stress for main-shaft bearings, the likelihood of subsurface cracking is reduced.

(3) Microstructure

Generally, plasma nitriding results in the formation of a compound layer (white layer) on the surface that is usually several microns thick. The compound layer, which is predominately iron nitride, is very hard and enhances the wear resistance of the material. However, the compound layer is friable and prone to break down under the influence of the high cyclic stresses experienced by a bearing during service. The process conditions developed by NSK-RHP are such that the formation of a compound layer on the surface is prevented.

Similarly, the plasma nitriding conditions developed do not result in the formation of grain boundary precipitates of carbonitrides. These can act in the same way as carbide networks to reduce the r.c.f. resistance.

(4) Distortion

Generally, thermochemical treatments such as nitriding and carburising cause distortion. It is important that the distortion produced as a result of the plasma nitriding process can be accommodated within the design of the bearing. Measurement of actual main-shaft bearing rings before and after plasma nitriding, see Table 2, has shown that the distortion is of the order of microns and can be allowed for in the design of the bearing.

(5) Residual stress

In addition to causing distortion, thermochemical treatments can produce residual stresses in the surface of the bearing rings. In the case of M50NiL material, carburising produces a high compressive stress in the carburised case that enhances the performance of the material. It is therefore important that the plasma nitriding does not adversely affect the residual stress in the materials.

Measurement of the residual stress in bearing raceways made in M50 and M50NiL materials has revealed that the plasma nitriding process increases the level of compressive stress in the surface. In the case of M50NiL, the compressive residual stress at the surface was increased on average by 400 MPa (Fig. 7). The effect on the depth profile was less pronounced with a slight increase in the level of compressive stress to a depth of around 0.5 mm (Fig. 8).

2.3.3 Fatigue testing

To assess the effect of plasma nitriding on the r.c.f. resistance of M50 and M50NiL under marginal lubrication, Polymet testing was carried out (Fig. 9).

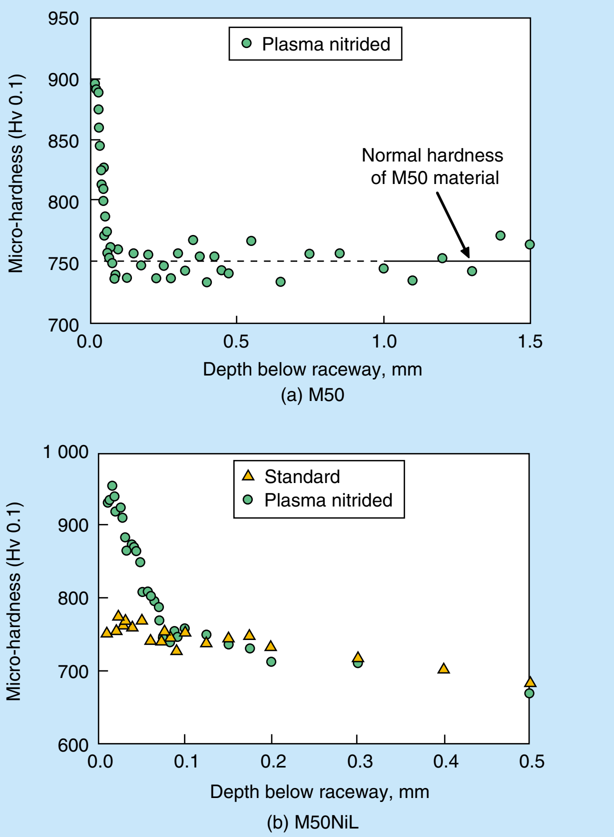


Fig. 6 Hardness profile of (a) M50 and (b) M50NiL before and after plasma nitriding

Table 2 Distortion by plasma nitriding

	Variance (µm)	
	Ring No. 1	Ring No. 2
Dimension:		
Outer diameter	+8	+6
Track	+6	+2
Width	+4	–
Bore	+4	–
Roundness:		
Outer diameter	+0.76	+0.65
Track	+1.03	+1.15

Ring No. 1, outer diameter = 283 mm
Ring No. 2, outer diameter = 181 mm

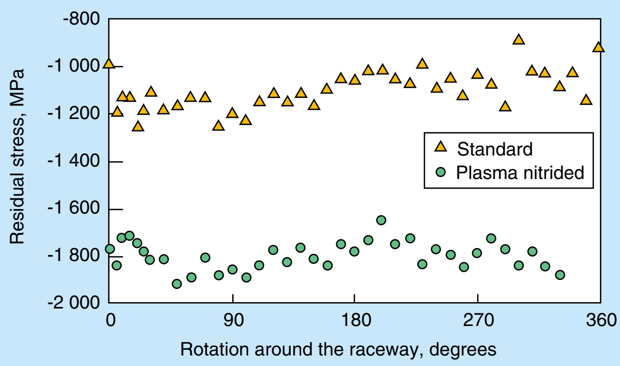


Fig. 7 Residual stress in the surface of M50NiL before and after plasma nitriding

In brief, the Polymet test involves the use of test specimens, nominally 9.5 mm in diameter by 76 mm in length. The specimens are diametrically loaded by two hardened M50 steel discs while rotating at a constant speed of 12 500 rpm. The maximum Hertzian stress induced in the test specimen by the discs is 4.8 GPa. The lubricant, synthetic gas turbine oil, is drip-fed from a reservoir onto the specimen/disc contact. The lambda value for the Polymet test is less than one, i.e., marginal lubrication.

The test normally continues until the test specimen fails by the generation of a r.c.f. spall. The results of the Polymet testing, plotted on the Weibull probability scale of cumulative percentage of failure versus number of stress repetitions, are shown in Fig. 10 and summarised in Table 3.

The baseline and plasma nitrided specimens were all made in material from the same cast and as part of the same manufacturing batch. The testing of the baseline and plasma nitrided specimens was interlaced to eliminate any variation caused by the Polymet test machine.

The results show that under conditions of high Hertzian contact stress and marginal lubrication, plasma nitriding has improved the r.c.f. resistance of both M50 and M50NiL materials. In the case of M50 material, the L_{10} life was increased by more than a factor of 10.

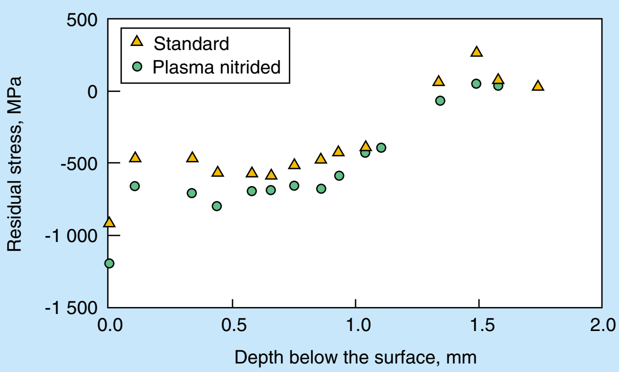


Fig. 8 M50NiL residual stress vs. depth profile before and after plasma nitriding

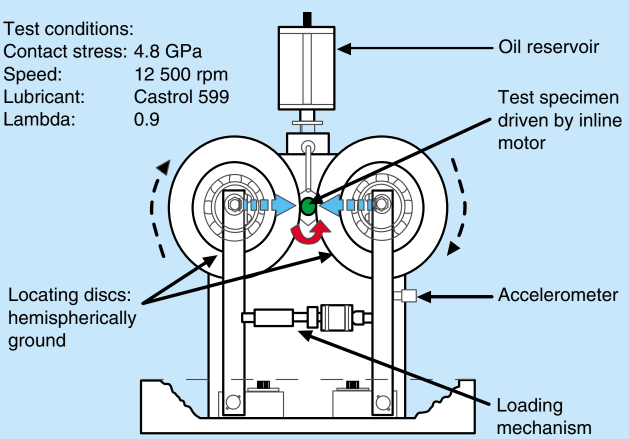


Fig. 9 Schematic of a Polymet test machine

2.4. Long-life material for high temperatures: "SHX"

The need for bearings that can perform at elevated temperatures is growing as machine speeds increase and the space in which bearings operate becomes more confined. The design of high-temperature bearings requires more care than the design of bearings for normal temperatures. NSK has analysed the failure of bearings operating at high temperatures and used the findings to develop new long-life bearing materials. SHX, with the required properties for use at high temperatures, is one of these newly developed materials.

2.4.1 Bearing properties required for high-temperature applications

Materials for bearings that operate at elevated temperatures require a number of properties. Among these is good dimensional stability. In the case of standard bearing materials, good dimensional stability is achieved by tempering at higher than normal tempering

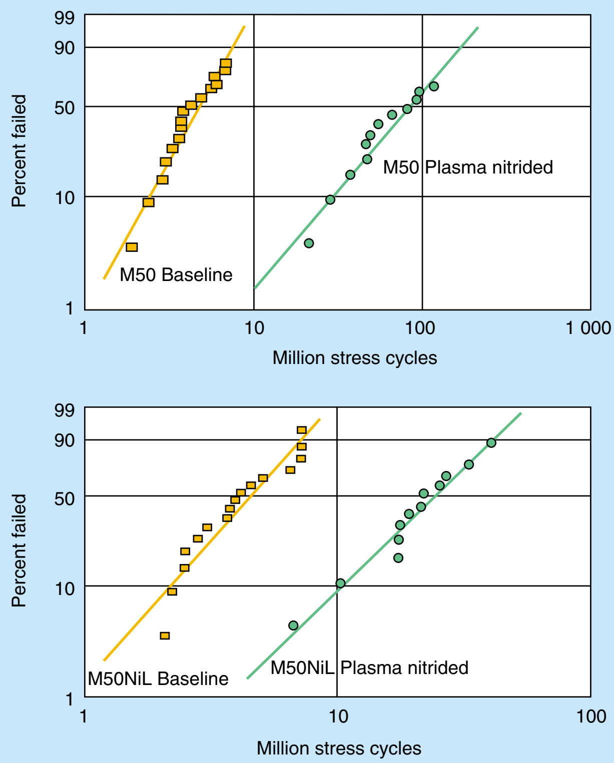


Fig. 10 Polymet results for plasma nitrided M50 and M50NiL materials

Table 3 Fatigue life test results

Material	Weibull analysis		
	Stress repetitions × 10^6		Slope
	L_{10}	L_{50}	
M50 Baseline	2.4	4.9	2.6
M50 Plasma nitrided	28.8	87.8	1.7
M50NiL Baseline	2.3	4.5	2.8
M50NiL Plasma nitrided	10.6	24.2	2.3

temperatures to remove the retained austenite. Such high-temperature tempering, however, causes a reduction in hardness and correspondingly, fatigue life (Fig. 11). Therefore, in the past, fatigue life has been sacrificed to gain good dimensional stability. Alternatively, more-expensive precipitation-hardening alloy steels have been used in place of standard bearing steel.

2.4.2 Process of fatigue at high temperatures

Research at NSK has revealed that fatigue at high temperatures can be divided in to two types: subsurface and surface. This is similar to fatigue under normal temperatures.[4] At high temperatures, however, it was discovered that the origin of failure in the case of subsurface fatigue was not just non-metallic inclusions but also areas of unusual microstructure (white microstructure).

It was also discovered that at high temperatures the frequency of surface fatigue was higher compared to normal temperatures. This is because the oil viscosity and correspondingly, the oil film thickness decrease as temperature increases. At high temperatures, the oil film thickness is often insufficient to prevent contact between the rolling elements and raceway, and therefore wear occurs. The process of this wear is accelerated by contamination of the lubricating oil by wear debris. It is important to pay sufficient attention to this type of surface fatigue as it can shorten life.

2.4.3 Development of long-life material

• Improving surface fatigue resistance

It is known that material factors like retained austenite, residual stress and surface hardness have an effect on surface fatigue resistance.[5] In the case of high-temperature applications, however, increasing bearing life by controlling the amount of retained austenite is not sufficient. This is due to the fact that the large volume of retained austenite responsible for long life is transformed at elevated temperatures, resulting in a reduction in dimensional stability.

As retained austenite has been ruled out as a way of improving the life of bearings used at high temperatures, the main focus has been on the control of residual stress and surface hardness. To create SHX steel, a suitable medium-carbon steel was carbonitrided to produce the required surface residual stress and its hardness was improved by adding elements that have a beneficial effect on tempering resistance, such as silicon and molybdenum. Also, the nitrogen introduced during carbonitriding produces an increase in surface hardness. Fig. 12 compares the relationship between hardness and tempering temperature of conventional steels and the new SHX steel.

• Improving subsurface fatigue resistance

In the case of subsurface fatigue it was discovered that the origin of failure at high temperatures was non-metallic inclusions and areas of unusual microstructure. To reduce the number of failures originating at non-metallic inclusions, the cleanliness of the steel was improved. To aid in improving steel cleanliness, NSK developed a new method for assessing steel cleanliness. This method makes use of extreme value statistics, and has been successfully utilised to improve the cleanliness of the new SHX material.

In order to prevent failures that originate from areas of unusual microstructure, an analysis was carried out to identify elements that delay changes in microstructure. The investigation revealed that silicon, molybdenum and nitrogen, which are already added to SHX to improve resistance to surface fatigue, also delay microstructural changes.

2.4.4 Other property requirements

In addition to good fatigue life, bearings that operate at high temperatures also need to have good wear and seizure resistance. This is because the formation of an oil film at high temperatures is difficult. Work carried out by NSK has shown that controlled additions of nitrogen can improve wear and seizure resistance.

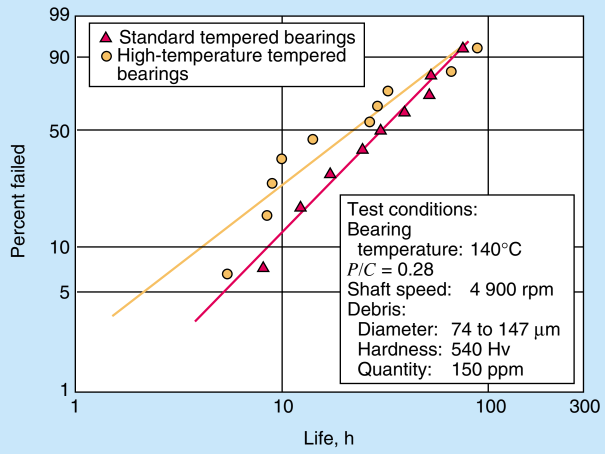


Fig. 11 Comparison of fatigue life under high temperature with contaminated lubrication (Surface fatigue)

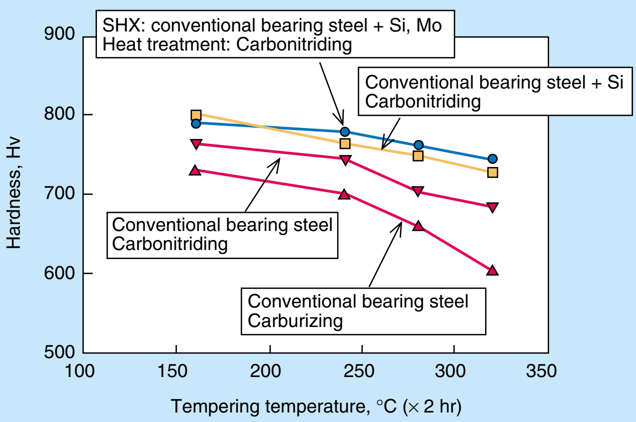


Fig. 12 Tempering resistance

2.4.5 Properties of SHX bearing material

Fig. 13 shows the dimensional change of SHX material as a function of time at both 140 and 200°C. As the figure shows, the dimensional stability of SHX material is slightly inferior to M50 but superior to conventional bearing steel tempered at high temperature.

Figs. 14 and 15 show the results of surface and subsurface fatigue life tests, respectively. Clearly, the resistance of SHX material to both surface and subsurface fatigue is superior to M50 and conventional bearing steel tempered at high temperature. The reason for the relatively low life of M50 material despite its high hardness is thought to be due to the large carbides it contains that have an adverse effect on fatigue life. Also the strength of the martensite matrix is reduced by the high-temperature tempering applied to the M50 material (>500°C).

Figs. 16 and 17 present the results of wear and seizure tests, respectively. As shown, the wear and seizure resistance of SHX material is superior to both M50 and conventional bearing steel tempered at high temperature.

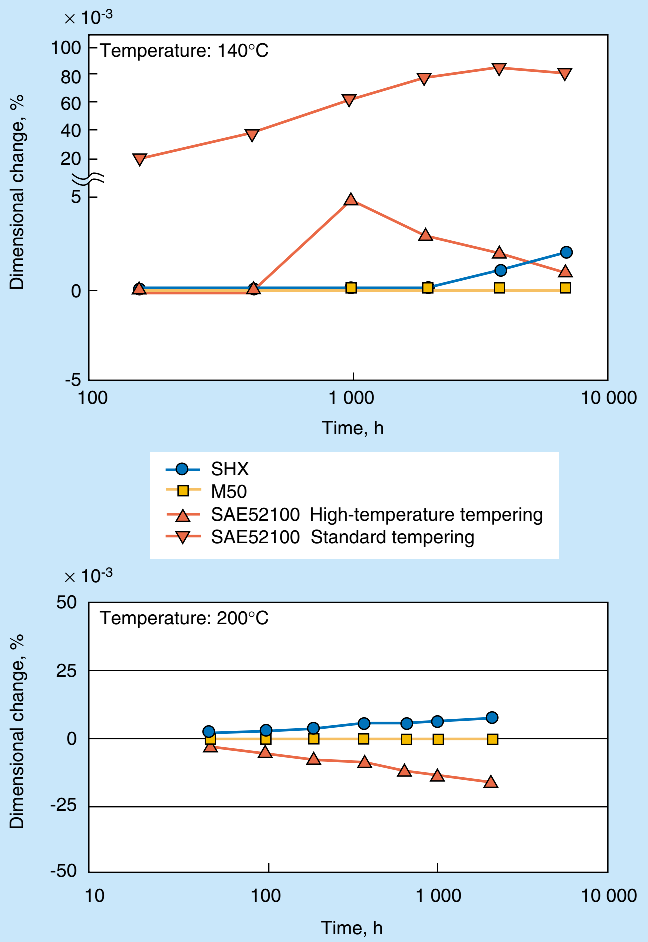


Fig. 13 Dimensional stability at 140°C and 200°C

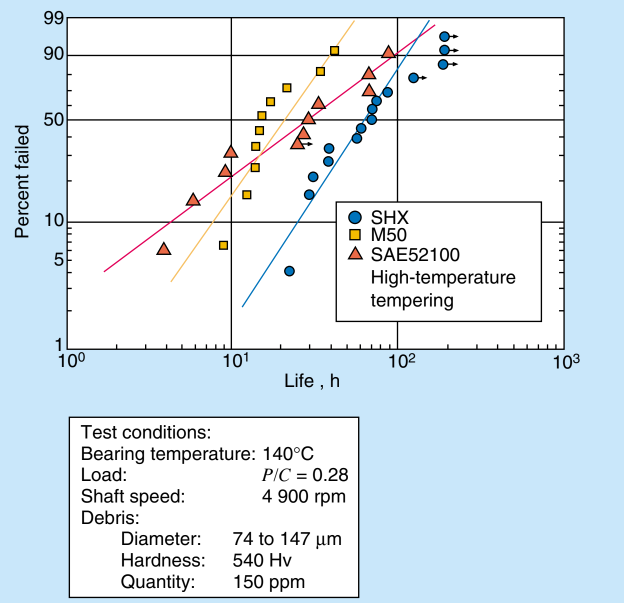


Fig. 14 Results of bearing fatigue life tests under high temperature with contaminated lubrication (Surface fatigue)

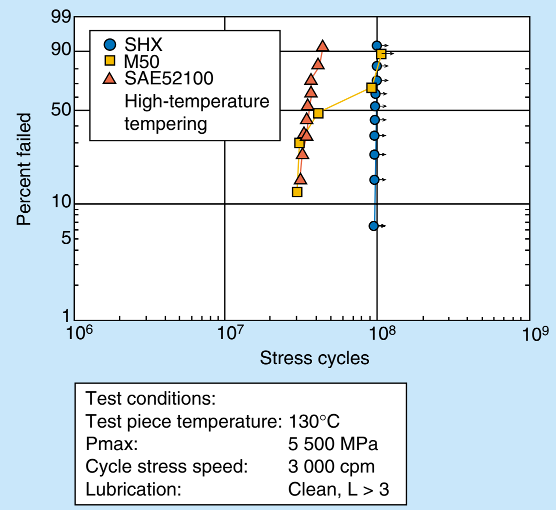


Fig. 15 Results of rolling element fatigue life test (Flat washer type test) under high temperature with clean lubrication (Subsurface fatigue)

3. Conclusion

Part 1 of this article, which appeared in the preceding issue of *Motion and Control*, focused on key operating requirements and the latest countermeasures for aircraft gas turbine engine bearings. Complementing Part 1, this paper has explained some new technologies developed for the improvement of the internal quality of the bearings. These new technologies include:

- A testing method that for the first time enables the quantitative evaluation of the relationship between hoop stress and inner ring fracture life

  This testing method was used to demonstrate that

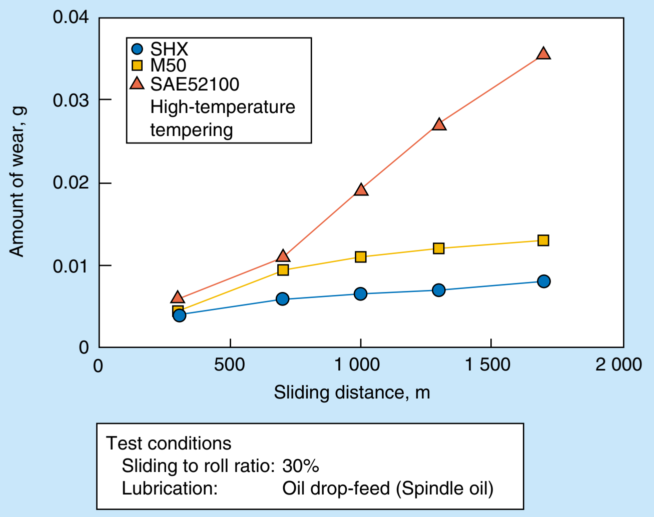


Fig. 16 Wear resistance (Two-cylinder wear tester)

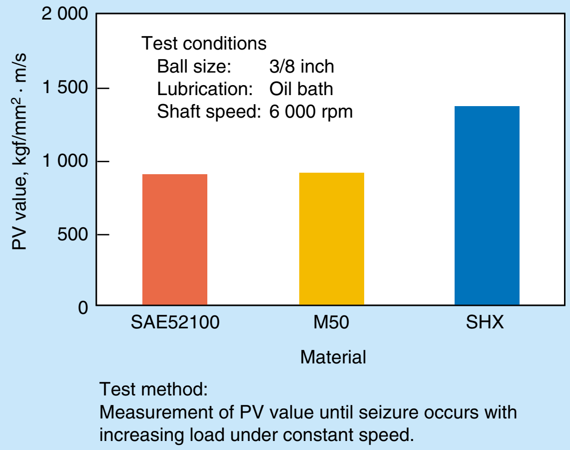


Fig. 17 Seizure resistance (4-ball test)

M50NiL steel has longer fatigue crack life than M50 steel.

• A plasma nitriding process for M50 and M50NiL main-shaft bearing materials

This process increases the surface hardness to around 975 Hv and produces a nitrided case depth between 25 and 75 µm. The process conditions are such that the formation of a compound layer on the surface is prevented and distortion is kept to a minimum. Consequently, plasma nitriding can be applied to the bearing components as the last process in their manufacture, with no subsequent machining required. Results of rolling contact fatigue testing showed that plasma nitriding produces a significant improvement in the r.c.f. life of both M50 and M50NiL materials under marginal lubrication. In the case of M50 material, the L_{10} fatigue life was increased by more than a factor of 10.

• A new bearing material for use in high-temperature conditions

The material, called SHX, not only has superior fatigue strength but also better wear and seizure resistance than conventional bearing materials.

The need by engine manufacturers to increase performance while reducing cost and weight continues to be a primary motivation behind R&D efforts. Development of bearing technology for materials, surface treatments and design is ongoing at NSK-RHP.

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Electric Power Steering (EPS)

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1. Introduction

The effects of global warming are becoming increasingly apparent. As a result, we product engineers are being asked to develop products that are more friendly to the earth's environment. Electric power steering (EPS) is such a product. By using power only when the steering wheel is turned by the driver, it consumes approximately one-twentieth the energy of conventional hydraulic power steering systems and, as it does not contain any oil, it does not pollute the environment both when it is produced and discarded. While offering these environmental benefits now, in the future EPS is expected to facilitate automatic steering—user-friendly technology that should ultimately reduce traffic accidents. Additionally, the software built into the EPS controller results in high performance and easy tuning during the development of prototypes of EPS systems. Because of these advantages, EPS has drawn the attention of automobile manufacturers all over the world. The EPS systems we produce have the highest market share not only in Japan but in Europe as well. This report outlines the construction of the column-type and pinion-type EPS systems produced by our company, as well as gives a technical profile of their main components: electronic control unit (ECU), sensor and motor.

2. EPS System

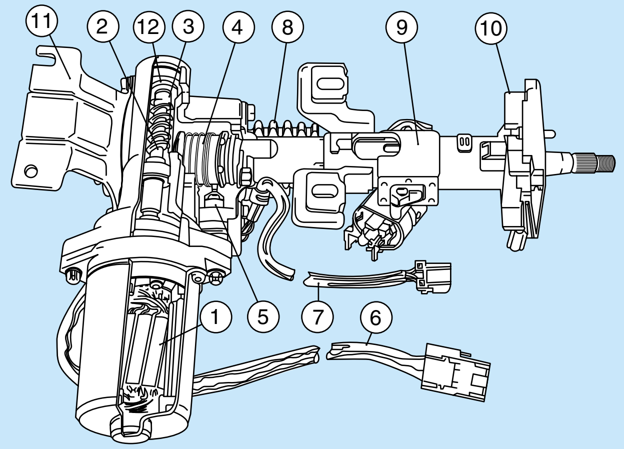
The EPS system consists of a torque sensor, which senses the driver's movements of the steering wheel as well as the movement of the vehicle; an ECU, which performs calculations on assisting force based on signals from the torque sensor; a motor, which produces turning force according to output from the ECU; and a reduction gear, which increases the turning force from the motor and transfers it to the steering mechanism. EPS is available in two types: a column type in which the reduction gear is located directly under the steering wheel, and a pinion type in which the reduction gear is attached to the pinion of the rack and pinion assembly. Each type of EPS system is speed-sensitive—vehicle speed and engine rotation signals are input from the vehicle into the ECU. Fig. 1 shows a vehicle with column-type EPS.

Fig. 1 A vehicle with column-type EPS

3. General Description of Column-Type EPS System

3.1 Construction of column-type EPS

Fig. 2 shows the construction of the column-type EPS system. Collapsible safety columns are usually used. The unit is contained in the dashboard.



1. Motor
2. Worm gear
3. Worm wheel
4. Torque sensor mechanism
5. Potentiometer
6. Motor harness
7. Torque sensor harness
8. Energy-absorbing convoluted tube
9. Keylock assembly
10. Switch bracket
11. Lower bracket
12. Rubber damper

Fig. 2 Construction of column-type EPS system

3.2 Column-type EPS series

Already ten years have passed since our column-type EPS systems were introduced in mini-cars (<0.66ℓ engine capacity). During this period, we have worked to increase their applications in mini-cars and to expand their range of applications into small vehicles (approximately 0.66 to 1.5ℓ engine capacity). As a result, our series of column-type EPS systems is now being used by automobile manufacturers in Japan and overseas. Table 1 lists four column-type EPS systems.

Table 1 Column-type EPS

	Reduction gear ratio	Electric current (A)	Assist torque (N·m)
A	16.5	25	17.3
B	16.5	30	19.8
C	17	30	25.0
D	18	45	33.5

3.3 Output improvement and energy-absorbing mechanism

a. Response to output improvement

In response to the improved output of EPS, we reviewed current design standards with a focus on improving endurance and impact strength. As a result, new design standards compatible with the higher output of today's EPS systems are now in place for the following components:

- worm and worm wheel gears
- output shaft
- bearing
- joints and connections
- mounting bracket

In addition, we achieved the serialized production of plastic worm wheel gears and, through the use of cold forging, reduced the cost of producing sensor system components such as the output shaft.

b. Energy-absorbing mechanism

Generally, with column-type EPS systems, there is less space available for the steering column to absorb energy in the event of an accident because the EPS system is located on the column. However, based on the safety column technology we have cultivated, we have developed an EPS equipped with an energy-absorbing mechanism, motor, gears, torque sensor system, key lock housing, and switch bracket, in spite of the fact that the overall length from the input shaft end to the output shaft end is restricted by the layout of vehicles (see Fig. 2). The column assembly of this EPS system has inner and outer column sections like a conventional EPS. In addition, for added safety in accidents, it has a mechanism to soften its collapse, a convoluted tube to absorb the driver's energy, and a device that allows the lower bracket to absorb energy.

3.4 Reduction gear and rattling noise

Because the steering wheel and reduction gear in a column-type EPS are located close to each other, sound produced in the reduction gear is directly transferred to the vehicle interior, to the detriment of driving comfort. To reduce this noise, our worm wheel gear is made of plastic. Moderate backlash is generally necessary for the meshing of gears, but the rattling noise of the gear teeth caused by backlash can be particularly troublesome when the vehicle is running on a bad road. As today's vehicles are required to be increasingly quiet, column-type EPS systems, which are located in vehicle interiors, must operate with minimum noise.

3.5 Reducing rattling noise

The rattling noise is caused by the teeth of the worm and worm wheel gears colliding as a vehicle is running on a bumpy irregular road. The noise, which may sometimes be perceived as self-excited vibration, becomes more noticeable as backlash increases. As backlash is unavoidable with reduction gears, we developed an impact absorption system that considerably reduces the rattling noise backlash generates.

A) Measures for reducing rattling noise

Elimination or reduction of teeth noise

- Lower backlash value
- Impact absorption by elastic material
- Review of gear specifications to reduce teeth noise

B) Optimum specifications for significant reduction of rattling noise

To absorb impact effectively

- Determine appropriate rigidity of rubber damper (Fig. 3)
- Determine sufficient volume of rubber for impact absorption

C) Reliability (endurance and strength)

To achieve high reliability

- Ensure rubber's resistance to deterioration (deformation from heat and repeated use)

D) Utilization of rubber damper characteristics

Rubber damper applications:

a. Impact damping
   Cushioning impacts of stopper by utilizing the low impact resilience of rubber

b. Vibration absorption
   Vibration attenuation in resonance region by utilizing the energy-absorbing property of rubber

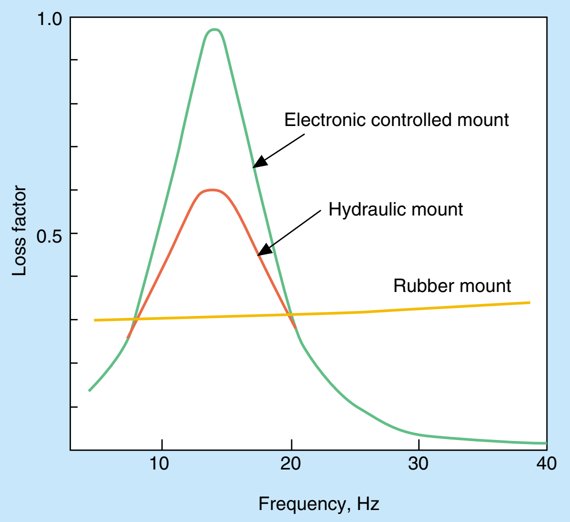


Fig. 3 Characteristics of impact-damping rubber mounts

Rubber characteristics required for impact damping:

a. Large loss factor (Fig. 3)
- Rubber material (physical properties)
- Volume of rubber
- Shape of rubber mass

b. Resistance to surrounding factors
- Heat resistance
- Resistance to deterioration from aging (deformation from fatigue)
- Resistance to year-round weather conditions
- Resistance to oils

3.6 Construction of column-type EPS system with rubber damper

Fig. 4 shows the section of an EPS system with a rubber damper. The rubber damper effectively reduces the amount of external force transferred from the tires to the worm wheel and worm gears. Taking into consideration the results of past studies, the rubber damper is mounted on the worm gear shaft, and a bush is used between the bearing and the worm gear shaft. This arrangement allows the rubber damper to absorb the external force by sliding along the worm gear shaft.

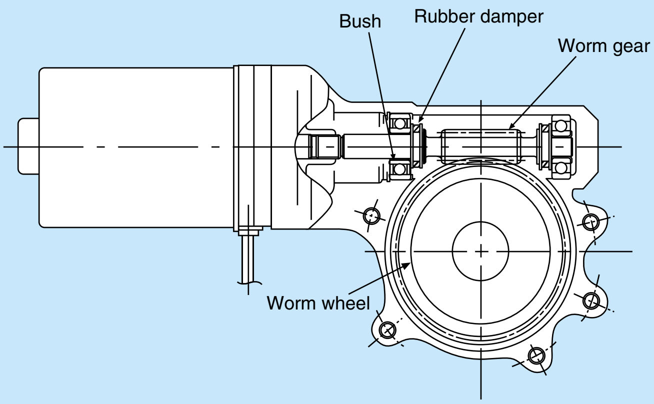


Fig. 4 Section of EPS system with rubber damper

3.7 Evaluation of rubber damper

Figs. 5 and 6 present frequency analysis results from a bench test on the effectiveness of the rubber damper.

In an endurance test of an EPS system without a rubber damper in an actual vehicle, the backlash naturally increased. When the backlash exceeded a certain level, the rattling noise began to be audible to the driver. However, in an endurance test of an EPS system with a rubber damper in an actual vehicle, the rubber damper system was found to suppress the rattling noise even when excessive backlash was produced.

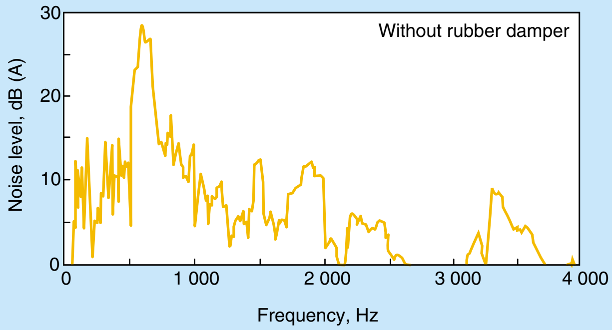


Fig. 5 Frequency analysis results from bench test without rubber damper

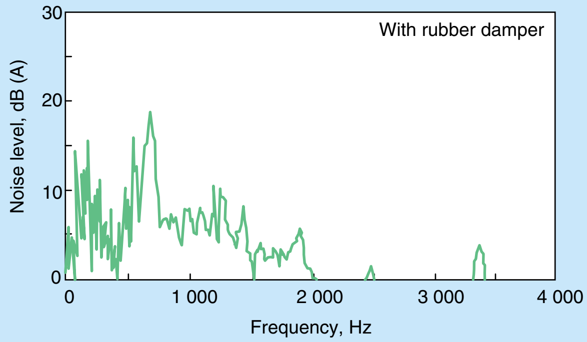


Fig. 6 Frequency analysis results from bench test with rubber damper

4. General Description of Pinion-Type EPS System

4.1 Construction of pinion-type EPS

Fig. 7 shows the construction of the pinion-type EPS system. In terms of the ability to withstand crashes (particularly secondary impacts), pinion-type EPS has an advantage over the column-type in that the impact-absorbing columns currently in use can be used as they

Table 2 Main specifications of pinion-type EPS

Maximum rack thrust		> 4.48 kN
Gear specifications	Stroke ratio	39 mm/rev
	Rack ratio	126 mm
	Lock to lock	3.23 rev
Reduction gear	Type	Plastic worm and worm wheel
	Reduction ratio	17
Motor	Type	DC brush motor
	Rated current	35A
	Rated speed	1210 rpm
	Rated torque	1.76 Nm
Torque sensor	Type	Non-contact self-induction
	Rated voltage	DC 12V
Controller	Rated voltage	DC 12V
	Control range of motor current	0 – 35A
	Control items	1) Differential compensation 2) Friction compensation 3) Astringent control

are. Pinion-type EPS, like the column-type EPS, consists of a torque sensor, reduction gear, motor, rack and pinion. The auxiliary power of the motor is directly transferred to the pinion shaft. The pinion-type gear assembly is located in the engine compartment so it is made very durable to enable it to endure the heat from the engine as well as water from outside the vehicle. The ECU, on the other hand, is located in the vehicle interior and is therefore free from the influence of heat and water. To help make the system lightweight and compact, the motor is small and the reduction gear has only one stage. Pinion-type EPS is available in various sizes for different motor outputs from 25A to 60A. The pinion-type EPS system was developed for small cars. Its main specifications are listed in Table 2.

4.2 Construction and characteristics of steering gear assembly

1) Comprising a worm and worm wheel gear, the reduction gear has reliable performance already proven on the market. The worm and worm wheel gear are made of glass fiber-reinforced plastic resin with improved strength at high temperatures. For the protection of the plastic gear, a torque sensor is incorporated on the motor shaft to prevent the application of torque higher than a certain level.

2) For application to the EPS, we developed a non-contact self-induction torque sensor with improved performance and endurance. The sensor circuit is contained in the gear assembly and therefore protected from extreme temperatures, radio waves and exposure to water. The principle of operation and the construction of this torque sensor are detailed in a following section.

3) Based on accumulated technology for manual steering mechanisms, the rack and pinion combination is designed to have high wheel-end impact strength and high endurance, with the effects of motor inertia peculiar to EPS taken into consideration.

4) To prevent the rattling noise generated by the tires, the design of the support yoke employs both a coned disk spring that applies pressure around the circumference of the support yoke and a center spring. To reduce the sliding resistance and wear of the rack, a sheet of specially formulated PTFE (polytetrafluorethylene) is employed.

5. ECU

Photo 1 shows the ECU. The three primary roles and corresponding functions of the ECU in EPS systems are:

1. Assurance of comfort
   Power steering functions
   (Motor current control function)
2. Assurance of safety
   Self-diagnosis and fail-safe functions
3. Assurance of convenience
   Communication functions

Table 3 details the functions of the ECU.

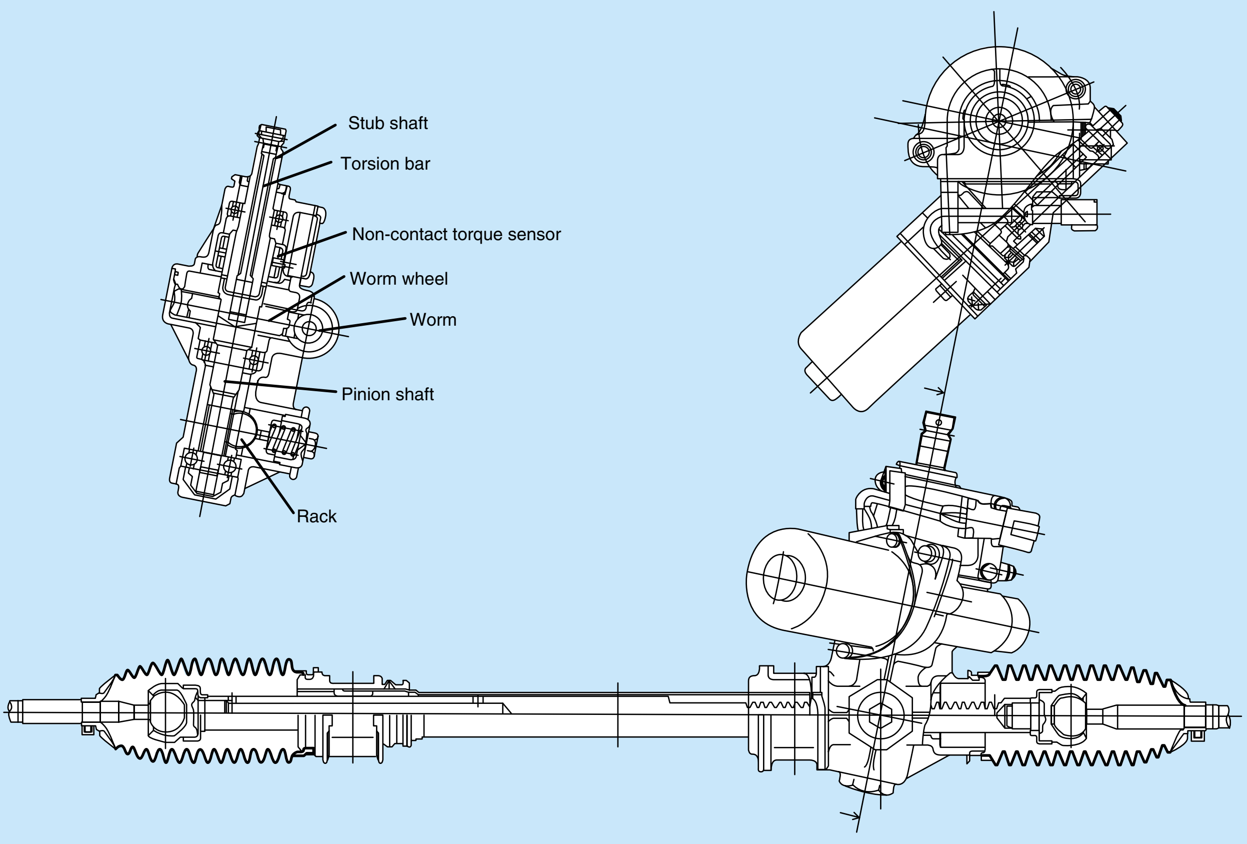


Fig. 7 Construction of pinion gear assembly

Table 3 Functions of ECU

Power steering functions The ECU controls motor current as shown in Fig. 8, Control block diagram.	
(1) Target base current operation	Generates assisting force (motor current) pursuant to vehicle speed and input torque to ensure appropriate steering power throughout vehicle speed range.
(2) Differential control	Minimizes fluctuations in steering power by compensating motor current in response to input torque fluctuations.
(3) Friction compensation	At low speeds, by compensating motor current, helps the steering wheel return to the straight position after having been turned.
(4) Convergence control	At high speeds, stabilizes the behavior of turned steering wheel (e.g., while changing lanes) by compensating motor current to make the steering wheel return to the straight position smoothly.
(5) Maximum motor current operation	Limits maximum motor current to the optimum level to protect ECU and motor from being damaged by motor's overheating.
Self-diagnosis and fail-safe functions	
Self-diagnosis function Fail-safe function	Monitor the EPS system components for failure. Upon detecting any failure, controls EPS functions depending on the influence of the failure and warns the driver. Also, stores the failure location in the ECU.
Communication functions	
Data communication function EPS testing function	Data stored in the ECU (ID code, date of manufacture, failure data, etc.) can be read and EPS system functions checked using external communication equipment.

Photo 1 ECU

6. Non-Contact Torque Sensor

6.1 Advantages of non-contact torque sensor

In our column-type EPS, primarily for reasons of reliability and cost, a potentiometer-type contact torque sensor is used. For the pinion-type EPS, we have developed a non-contact torque sensor. The position of the non-contact torque sensor is shown in Fig. 9. Compared to the conventional potentiometer-type contact torque sensor, the new non-contact torque sensor:

- is free of wear from aging
- has smaller hysteresis
- is less affected by runout and axial displacement of the shaft

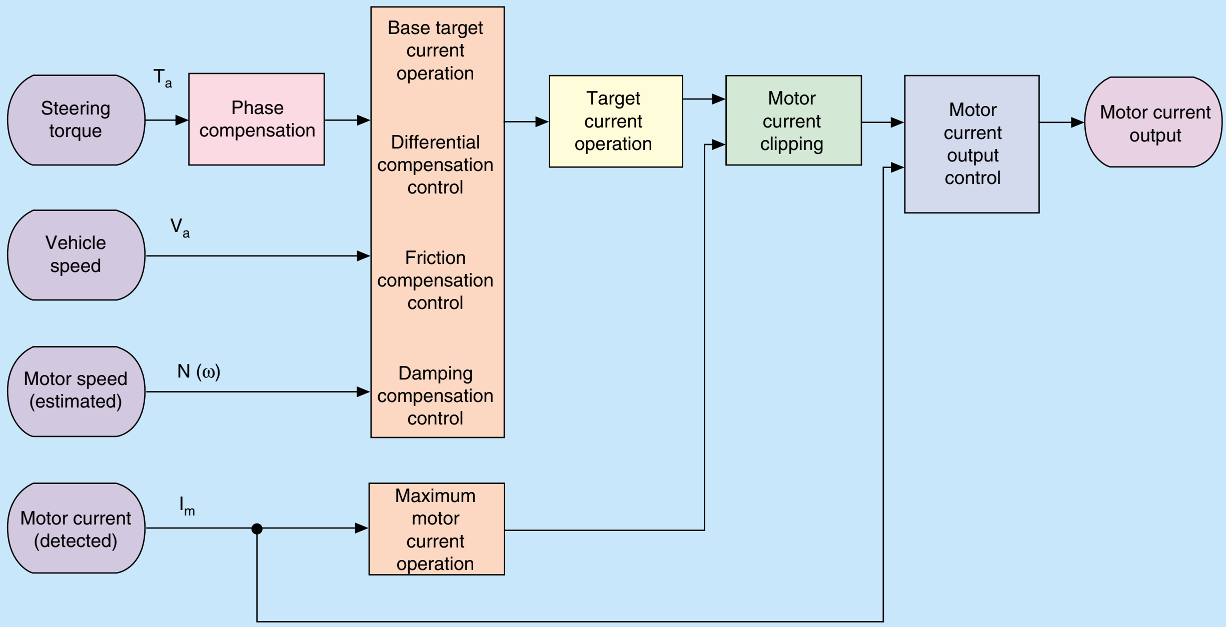


Fig. 8 Control block diagram

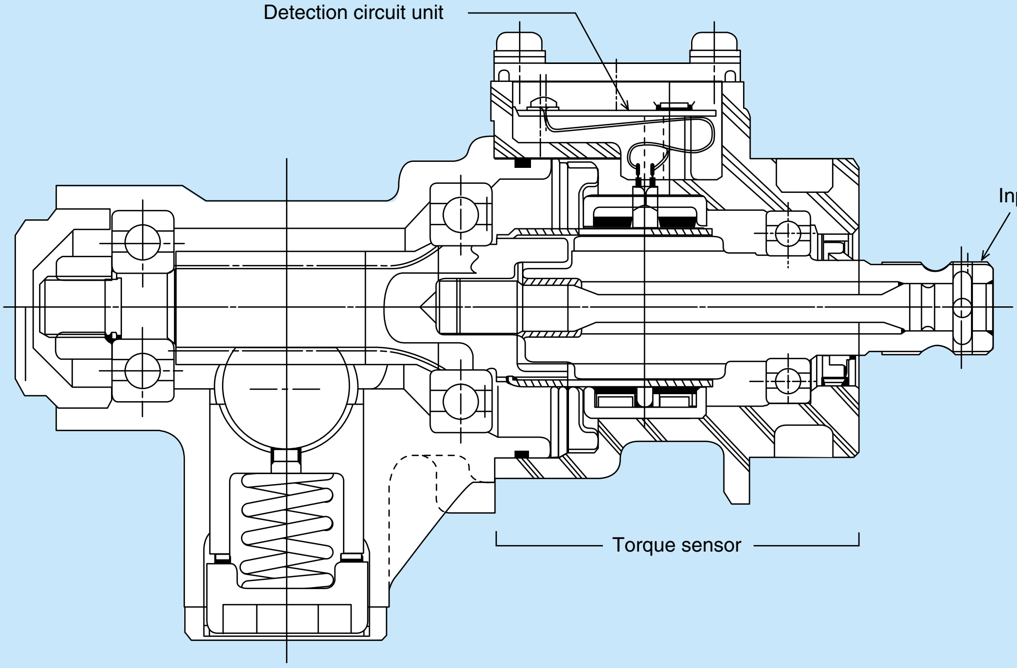


Fig. 9 Non-contact torque sensor in pinion-type EPS

6.2 Construction and principle of operation of non-contact torque sensor

Fig. 10 illustrates the construction of the non-contact torque sensor. The input shaft and output shaft are connected by a torsion bar. The input shaft has splines and the output shaft has slots. During steering, the relative displacement of the slots and splines is changed by an amount equal to the change in the torsion of the torsion bar, causing change in the amount of magnetization of the splines. If the two coils are then energized with AC, the changes in inductance of the two magnetic flux detecting coils become anti-phasic to each other because the pitches of the two rows of the slots in the metal sleeve are originally offset by an amount equal to half pitch. Differential amplification of the changes can double the output, while offsetting common mode components caused by temperature and other factors. As a result, the sensor has high sensitivity.

6.3 Basic operation of non-contact torque sensor circuit

Fig. 11 shows a block diagram of the torque sensor circuit. The current amplifier provides amplitude-constant AC to the resistor and coil bridge, but the coil terminal voltage varies depending on inductance variations caused by torque, as described in the foregoing section. Because the voltage variations are anti-phase to each other, only the difference between the changes is amplified and then the coil drive AC component is removed. In order to ensure that the ECU accurately recognizes zero torque, the circuit receives reference voltage from the ECU, corrects the voltage at zero torque, and outputs torque signals. To ensure high reliability, these two circuits are provided downstream of the coil.

The monitor checks for oscillator trouble, coil rupture and other faults and, on finding a fault, forces one signal only to output an anomaly value.

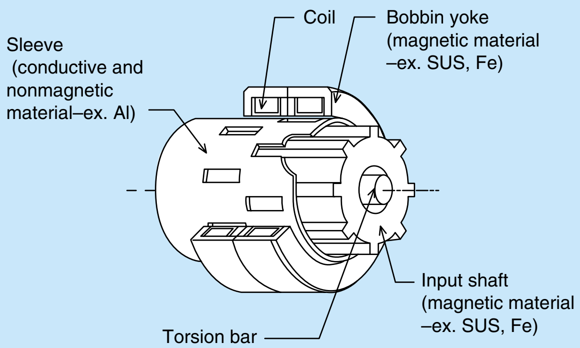


Fig. 10 Construction of torque sensor

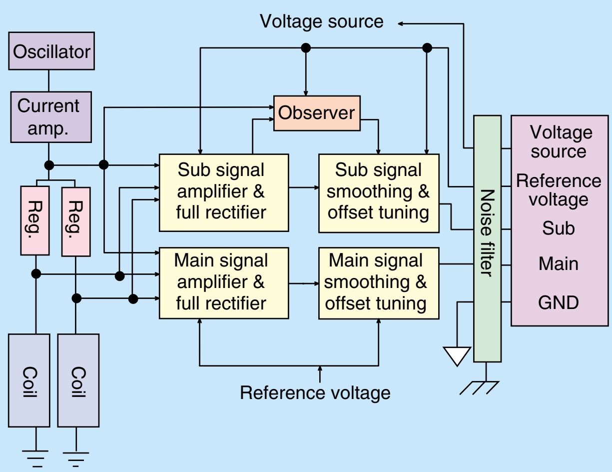


Fig. 11 Block diagram of torque sensor circuit

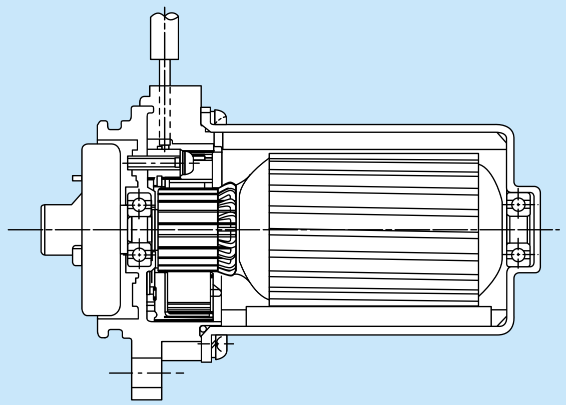


Fig. 12 Construction of new motor

7. Motor

The motor for EPS is a permanent magnetic field DC motor. Attached to the power steering gear assembly, it generates steering assisting force. This motor has the following operating requirements and features:

Operating requirements

- The motor must be able to generate torque without turning.
- The motor must be able to reverse its rotation abruptly.
- The fact that motor vibration and torque fluctuations are directly transferred through the steering wheel to the hands of the driver must be considered.

Features

- Small, lightweight and high-output
- Small fluctuations in torque during operation
- Very low vibration and noise
- Low inertia
- Low friction torque
- High reliability

We have developed a new motor with improved assisting performance and design and applied it to our EPS. Fig. 12 illustrates the construction of the motor. Compared to conventional motors, the new motor, while the same size, has approximately double the rated output torque and 43% higher rated output power. This is attributed to three factors:

- The high residual flux density of the magnet
- Multiple poles
- Increased armature coil winding density

Fig. 13 compares the rated capacities of the old and new motors.

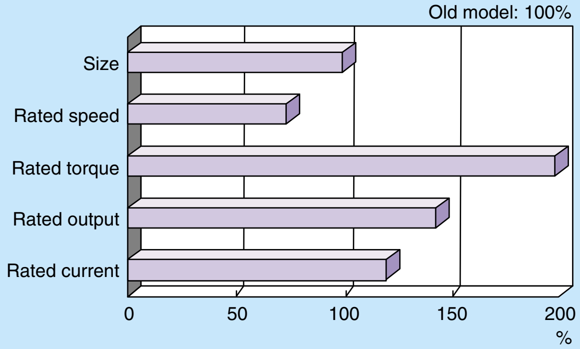


Fig. 13 Performance comparison between new and old motors

8. Conclusion

We have presented here the construction and features of our EPS systems. Just a decade old, EPS is still developing and improving, having only recently arrived at a level comparable to its predecessor, hydraulic power steering. To meet the needs of present and future users and thereby expand applications of EPS, our future efforts will be focused both on developing cost-reducing measures and on making further technical improvements such as reduced weight, higher output, and improved performance and functions.

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Recent Development of NSK Direct-Drive Motors

Sadatoshi Kato
Precision Parts and Machinery Technology Center

ABSTRACT

Almost 15 years have passed since NSK started to develop direct-drive motor systems. Today, having gained recognition as high-performance, reliable actuator systems, these products are used in a variety of industries, including in particular the semiconductor manufacturing machinery industry. This paper presents recent noteworthy developments in direct-drive motor technology. It focuses on improvements in the preciseness of positioning and the position monitoring method, and introduces automatic tuning, which shortens the time required to determine servo parameters. In addition, new product lines developed in response to the needs of the market are presented.

1. Introduction

Direct-drive (DD) motors, which are designed to drive loads directly without reduction gears, have been used for many years in home electric appliances, especially audio and video units and components, because of their advantages of high rotational accuracy, compactness and maintenance-free performance. With a view toward applying these advantages to industrial applications, NSK has been conducting research on DD motors, including Megatorque Motors, for almost 15 years.

In 1984, the introduction by US firm Adept Technology of DD robots with Megatorque Motors generated a great deal of interest in DD motors for industrial applications. Most of the early research and development on DD motors for industrial use focused on DD robots. Nowadays, however, DD motors are used in a rapidly expanding range of applications including semiconductor manufacturing equipment and machine tools. The growth in the application of DD motors is attributed to their improved performance, their reduced cost, and the extent to which their compact design, with built-in speed-reducing and load-carrying systems, facilitates the development of compact actuator systems with shorter lead times and therefore at lower cost. In short, the reputation of DD motors as high-performance, low-cost and easy-to-use actuators has been firmly established.

This report discusses recent technical development and trends in the field of DD motors. It first describes current industrial DD motors, then presents recent technical developments and improvements, and finally discusses new expectations and requirements for DD motors and NSK's response.

2. Types and Features of Industrial DD Motors

Fig. 1 shows the various types of DD motors.[1),2)] Each type of DD motor has its own respective features. NSK manufactures the following three types of DD motors:

- VR (variable reluctance) Megatorque Motor (a variation of the inductor type)
- VR Megathrust Motor (a linear Megatorque Motor)
- Permanent magnet (PM) linear motor (provides higher peak thrust than the VR type)

2.1 Features of industrial DD motors

(1) Direct current type

Direct current DD motors have high peak torque and high controllability but also maintenance-related drawbacks including the necessity of replacing brushes. Nowadays, this type of DD motor is not widely used.

(2) Permanent synchronized magnet type

Permanent synchronized magnet DD motors have basically the same features as the direct current type, but do not require maintenance such as brush replacement. Because of their good controllability, they are used as constant-speed high-accuracy air spindle motors in HDD production inspection systems. Generally, however, their applications appear to be relatively limited. In some cases where high torque is required, greater copper loss and motor overheating can be a problem. The cost of permanent magnets can also be a problem.

(3) Inductor type

With inductor DD motors, copper loss and cost can be reduced and continuous high torque is possible. Because of these advantages, inductor DD motors are currently the most widely used.

There are two kinds of inductor DD motors: variable reluctance (VR) and hybrid (HB). VR motors are simple

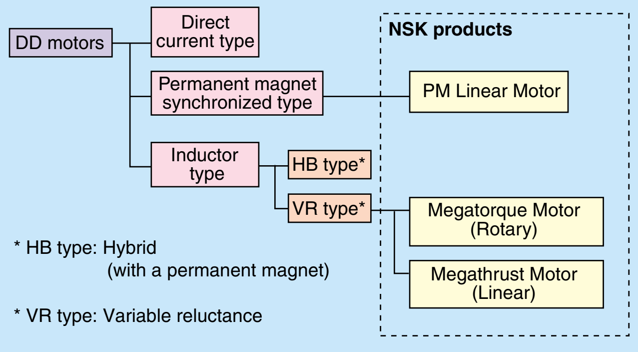


Fig. 1 Types of DD Motors

and do not have a permanent magnet. Formerly, they required a complicated controller to reduce torque ripples and improve controllability. Now, as a result of progress in control technology and the spread of high-performance CPUs, VR motors have satisfactory performance for a wide range of applications and are available at lower cost. They represent the majority of industrial DD motors. With HB motors, higher controllability is achieved by using a permanent magnet. However, permanent magnets inevitably involve a cost problem.

Research and development of new types of motors is an ongoing process. A recent result of this effort is the PM vernier motor.[3] To increase torque, this motor has permanent magnets embedded in between slots. While PM vernier motors are promising, manufacturing difficulties still must be overcome to realize their commercialization.

2.2 Features and recent development of NSK's Megatorque Motor

2.2.1 Features of NSK's Megatorque Motor

The NSK Megatorque Motor is a variable reluctance motor. It has been used for high-accuracy indexing in general industrial applications by virtue of the following features:

(1) As it does not employ a permanent magnet, it can be produced at lower cost.
(2) It uses a resolver for position detection and therefore has high position detection reliability while being mechanically sound and less vulnerable to oil mist.
(3) It has highly rigid built-in bearings and can bear loads directly.
(4) As its hollow structure provides space for tubing and wiring, the size of the system can be reduced.
(5) The built-in positioning function in the driver unit eliminates the need for a controller.[4] Along with features (3) and (4) above, this feature makes the motor well suited for use as an index unit and presents users with significant savings of labor and time in both design and manufacture.

Fig. 2 shows how Megatorque Motors can reduce the size of a whole system. In this example, the built-in positioning function in the driver unit is utilized to dispense with the controller (pulse train controller) and contribute to the compact construction of the control equipment.

2.2.2 Recent development of NSK's Megatorque Motor

Recent development efforts on the NSK Megatorque Motor have focused on improving essential performance characteristics (e.g., accuracy) and broadening its application range by reducing its cost and making servo gain adjustment easier. Specific improvements include:

- A drastic reduction in the number of component parts and an approximately 50% reduction in costs through the adoption of large-scale ASIC
- Making gain adjustment automatic by adding an auto-tuning function (described in section 3.2 below)

These improvements have been incorporated into NSK's YS Megatorque Motor and ESA Driver Unit (Photo 1). The YS Megatorque Motor and ESA Driver Unit together form an easy-to-use index available at a cost equivalent to or less than cam indexes that use general-purpose AC servo motors. As a result, Megatorque Motors have begun to be increasingly used, even in areas where traditional DD motors have not, such as automatic body-profiling equipment for custom-made clothes and remote-control parabolic antenna drives for construction machines.

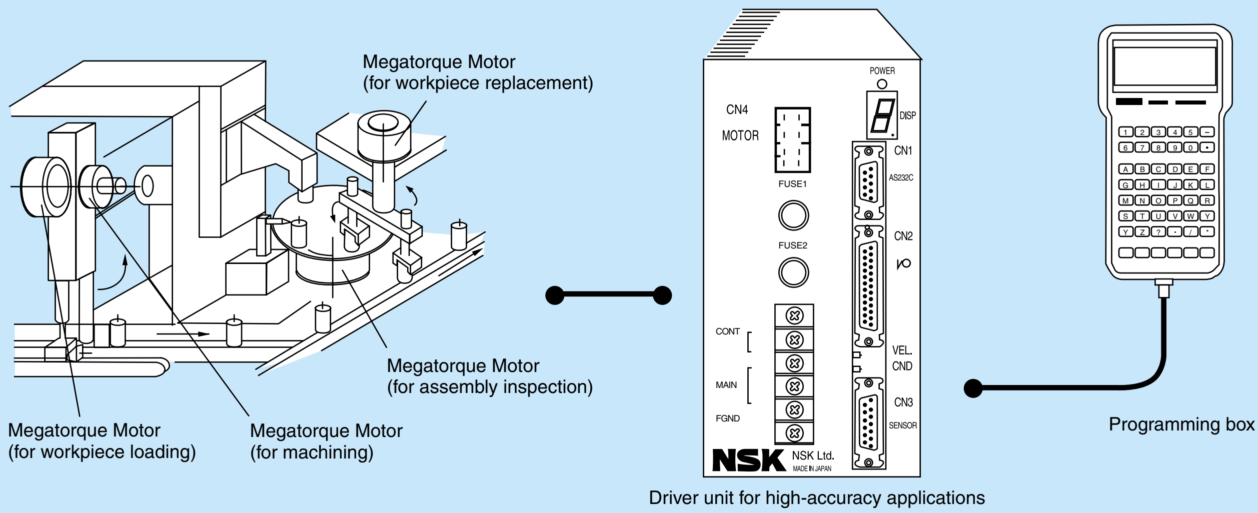


Fig. 2 Application example

Photo 1 YS series Megatorque Motor system

2.3 Features and recent development of NSK's Megathrust Motor

2.3.1 Features of NSK's Megathrust Motor

To create the Megathrust Motor, the principles and construction of the Megatorque Motor were applied to linear arrangements. The features of the Megathrust Motor are quite similar to those of the Megatorque Motor, but the Megathrust Motor is used in high-speed transfer systems for lightweight material. It has the following features:

(1) The resolver used in it as a position sensor contributes to the motor being compact, low-priced and environmentally friendly.

(2) A multi-slider system (Fig. 3) that can perform different operations simultaneously can be easily built up by installing independently controlled sliders on one rack base. In fact, multi-slider systems are used in more than 20 percent of Megathrust applications.

(3) Low particle emission (outparticling). Ball screws, which can emit particles during operation, are not used. When the Megathrust Motor is operated at a speed of 400 mm/s with its linear guides lubricated with NSK's clean grease, LG2, and without cover or suction, the level of particles emitted is not more than 100/cubic foot, measured downstream of the direction of the air flow (Fig. 4). The dominant application for the Megathrust Motor is in transfer systems on semiconductor and liquid crystal production lines.

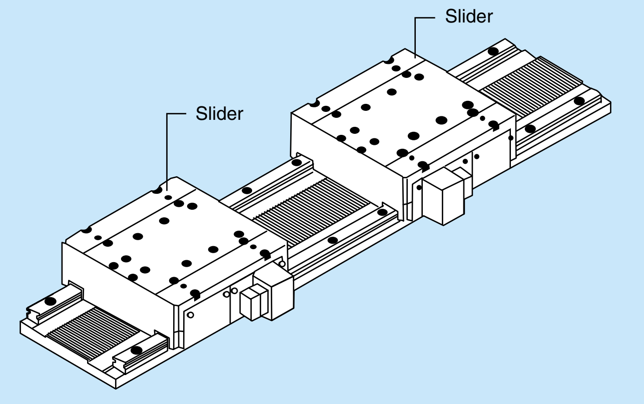


Fig. 3 Multi-slider of Megathrust Motor

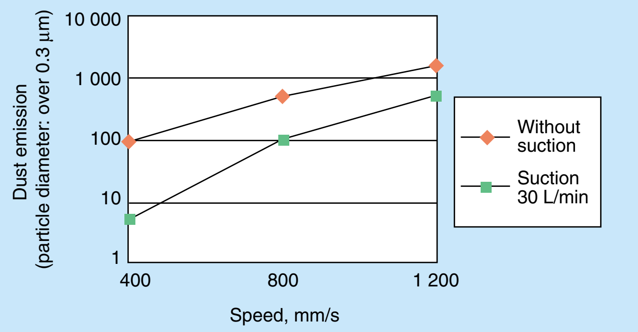


Fig. 4 Dust emission of Megathrust Motor (in down flow)

2.3.2 Recent development of NSK's Megathrust Motor

Recent development of the Megathrust Motor has been focused on two objectives: improving specific features such as its strength in the long-stroke high-speed transfer of lightweight materials; and, as with the Megatorque Motor, broadening the motor's application range by reducing production costs and making it easier to use.

If a ball screw, for instance, is used in the drive unit of a long-stroke high-speed transfer system, there exist limitations (i.e., critical speed and $d_m n$ value) on the rotational speed about the screw shaft. In order to make this system safely functional in this instance, special design arrangements such as large shaft diameter or very large lead are required. In contrast, the Megathrust Motor, whose highest speed is not restricted by stroke length, performs well in long-stroke high-speed transfer systems.

To meet the requirement of longer-stroke transfers, NSK has developed technology (including a method for coupling rack bases and a resolver that can work even at coupled joints of rack bases) for achieving a maximum stroke of 30 meters by coupling rack bases (stators). This technology is incorporated into the Y series Megathrust Motor. Additionally, the production cost of the Y series Megathrust Motor was significantly reduced by:

- A thorough reduction in the number of component parts and labor required for production by changing the method of constructing the rack base from conventional lamination to the machining (serration) of magnetic material
- Incorporating part of the resolver into the motor main body

Auto-tuning operation is also ensured because the Y series Megathrust Motor is used in combination with the ESA Driver Unit. As a result of reducing its cost and making it easier to use, the Y series Megathrust Motor is being employed in a broadening range of applications.

2.4 Examples of recent development of PM linear motor

While the Megathrust Motor presents advantages of low cost and long-stroke adaptability as described above, there are limitations on its performance in terms of higher acceleration and deceleration and greater thrust. For applications that require such attributes, NSK has developed its PM linear motor.

(1) Development for applications with higher acceleration/deceleration

Since the peak thrust of the Megathrust Motor is limited by magnetic saturation, the Megathrust Motor may not be able to fully exhibit its performance capabilities in applications where rapid acceleration/deceleration is required. Taking advantage of the high-thrust performance of PM linear motors,[5] NSK is in the process of improving on it to create a high-speed linear motor for use in an assembly process of semiconductor manufacturing. In this application, the motor is required to have both high acceleration/deceleration capability and high-speed performance.

(2) Development for applications needing greater thrust

Traditionally, industrial linear motors (except those for linear motor cars) were used mainly for high-speed and high-tact transferring of lightweight items. As a result, more attention was paid to reducing the weight of their moving parts than to increasing their thrust. Recently, the application of linear motors to quick-feed and light-duty cutting systems in machine tools has stimulated efforts to increase thrust. In order to do this, both the space allocated in the motor for thrust-generating parts and thrust generation per unit of area need to be increased. In these respects, the Megathrust Motor has its thrust limited due to magnetic saturation. By shortening the pole pitch to increase the thrust of the PM linear motor, NSK has developed a linear motor with a thrust capacity of 2 200 N (Fig. 5). Applications for this linear motor include mounters and high acceleration/deceleration transfer systems for light- and medium-weight items.

3. Recent Technical Development of DD Motors at NSK

As suggested previously, there are two basic trends in the ongoing research and development of DD motors: improved performance and expansion of applications by reducing the cost of DD motors and making them easier to use. The following sections present specific examples of work carried out at NSK in each of these two areas.
The examples focus on position detection for high-accuracy positioning (improved performance), and auto-tuning (expanding applications by making DD motors easier to use).

3.1 Position detection for high-accuracy positioning

High-accuracy positioning technology has been drawing attention recently due in part to recent increases in the size of workpieces (typically semiconductor wafers and liquid crystal substrates). Peripheral parts of these larger workpieces may lack accuracy after positioning if the positioning is carried out with previous levels of accuracy. Additionally, semiconductors and liquid crystal displays are increasingly being patterned finer, and office automation equipment, communication equipment and consumer instruments and appliances are being made lighter and smaller. These trends further necessitate the higher positioning accuracy of DD motors. In the next few sections we report on NSK's response to the need for higher positioning accuracy—the VR multipolar resolver used in the Megatorque Motor.

3.1.1 VR multipolar resolver: features and process of position detection

Optical encoders are widely used as position sensors in general-purpose AC servo motors. However, optical encoders with high enough accuracy and resolution to meet requirements for DC motors may be too costly and/or present environmental problems. The VR multipolar resolver used in the Megatorque Motor is able to achieve

1. Motor specifications	
Maximum thrust	2 200 N
Stroke	930 mm
Mass of slider	26.8 kg
Resolution of position sensor	0.5 µm
2. Performance	
Sliding distance	100 mm
Maximum speed*	600 mm/s
Acceleration/deceleration	1.0 G
Mass of load	150 kg
In-position width	±5 µm
Positioning time**	Approx. 243 ms

* Due to limitations imposed by the linear scale
** Including setting time of approx. 20 ms

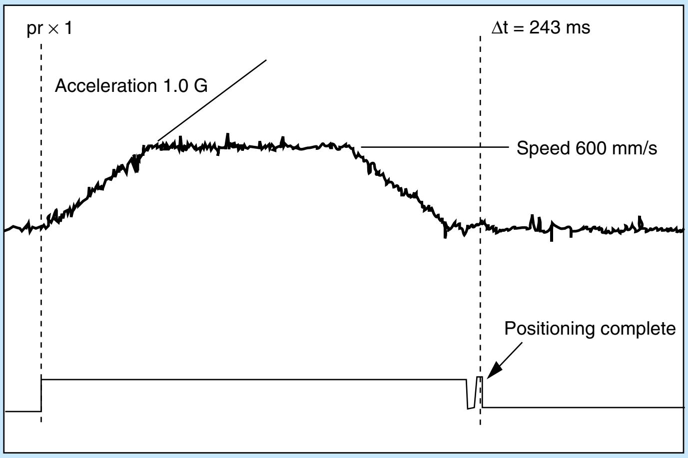


Fig. 5 Positioning of high-thrust PM linear motor

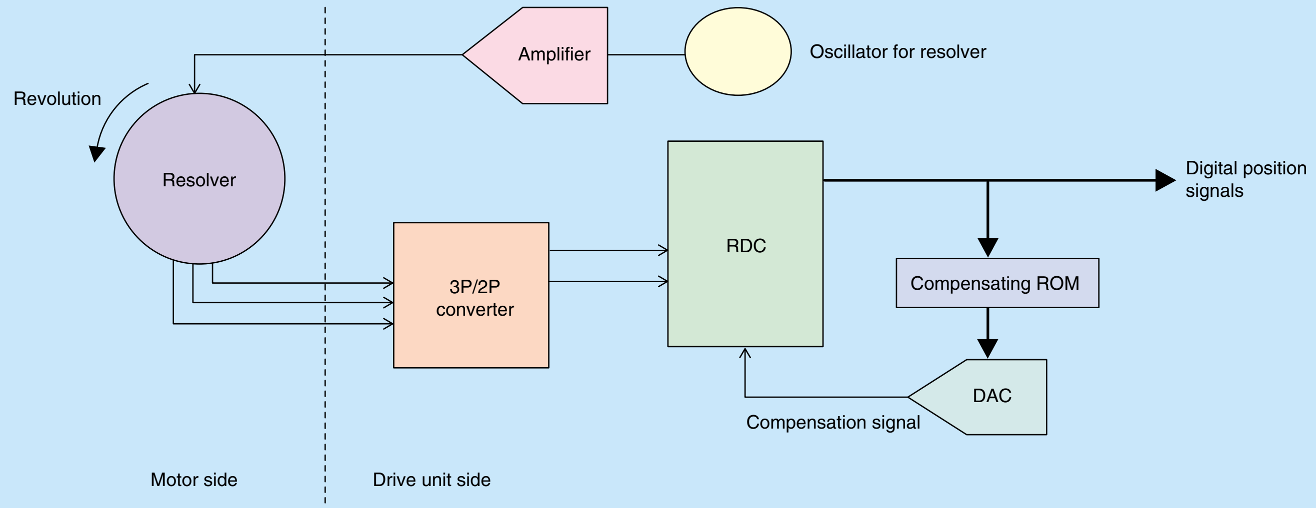


Fig. 6 Position detection circuit

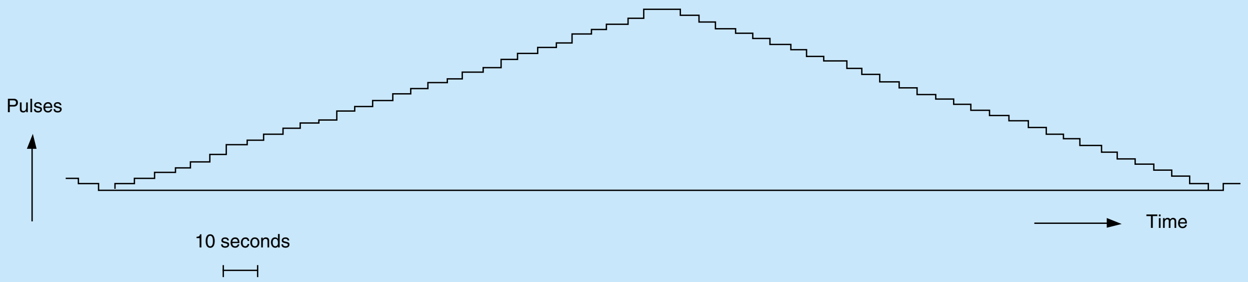


Fig. 7 Step feed positioning accuracy of ultra-high resolution Megatorque Motor (1 966 080 steps)

high resolution relatively easily. It has the following features:

- The multipolar construction of the resolver, with the same number of poles as the motor, provides an absolute position within an electrical angle to facilitate the commutation control of the motor current.
- Being integrated with the motor, the resolver needs no coupler or coupling arrangements and is free from backlash, assuring high accuracy.
- The resolver is highly reliable because it is insensitive to vibration, temperature or oil mist.

The process of position detection by the resolver

The rotor, which has 100 to 150 serrate teeth at equal pitches on its circumference, is paired with the stator, which has 3-phase windings. As the rotor rotates, the variation of permeance between the stator and the rotor serration causes the inductance of the stator wires to vary by one cycle (= 360° in electrical angle) per pitch turn of the rotor teeth. From this variation in inductance, one 10-bit or 12-bit digital positional signal per electrical angle of 360° can be obtained through the medium of the RD converter (RDC) located in the signal-processing circuit of the resolver. With 12-bit signals and, for example, 150 teeth, a position detection resolution of 150×2^{12} = 614 400 pulses/revolution is obtained. Fig. 6 is a block diagram of the position detection circuit used in the Megatorque Motor.

3.1.2 Improvement in resolution of VR multipolar resolver

The resolving power of the VR resolver can be increased through two methods: increasing the number of polar teeth of the rotor or improving the resolving power of the RDC. Improving the RDC resolution is more effective than increasing the number of teeth, and has the advantage of requiring no geometrical changes to the motor. Presently, NSK is developing DD motors with a 14-bit resolution resolver.

Fig. 7 shows actual one-pulse feed positioning measurements obtained through the 14-bit resolution developed by NSK. (In this example, the process is divided into 120×2^{14} = 1 966 080 steps because the rotor has 120 teeth.) The figure clearly shows that positioning per pulse feed is accurately performed without backlashes.

To evaluate positioning accuracy, the Megatorque Motor was turned clockwise and then counterclockwise in steps of one pulse each for a total of 30 pulses. At the same time, the respective minute angle of each turn was measured by a gap sensor in terms of shift distance at a point 140 mm from the center of rotation of the motor (Fig. 8).

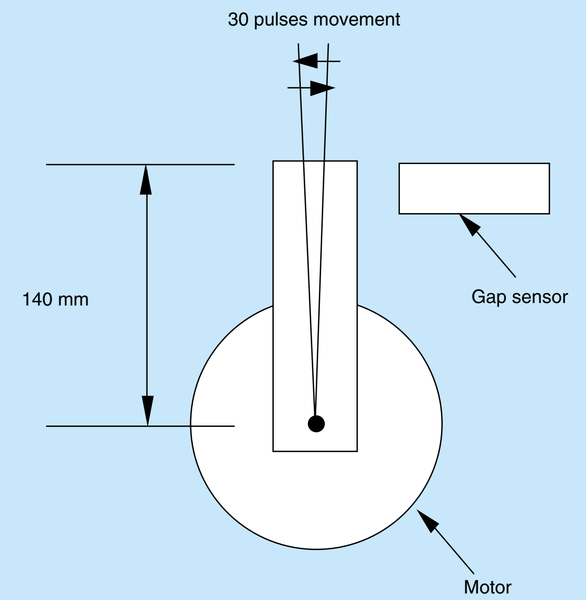


Fig. 8 Measuring of position accuracy

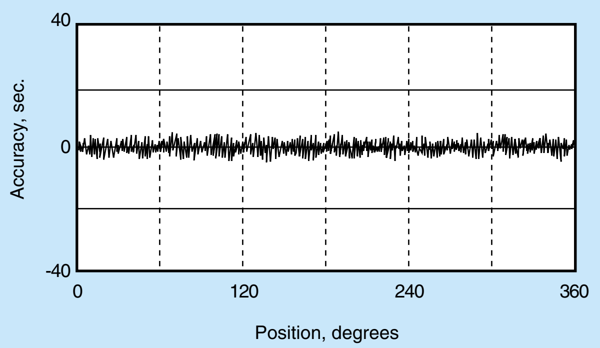


Fig. 9 Positioning accuracy of standard SSB014 type Megatorque Motor

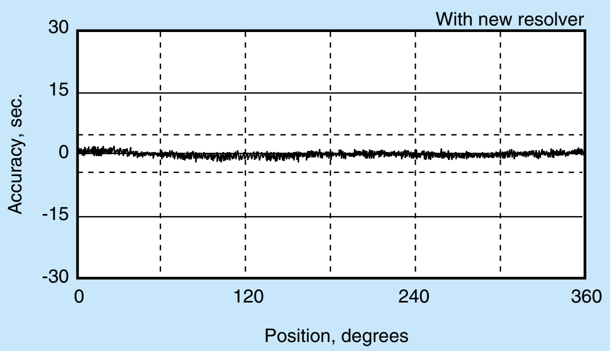


Fig. 10 Positioning accuracy of SSB014 type Megatorque Motor with new resolver

3.1.3 Improvement in accuracy of VR multipolar resolver

As shown in the block diagram in Fig. 6, the high positioning accuracy of the Megatorque Motor is assured by the accuracy compensation of the position sensor. However, the compensation is not enough to fully satisfy recent demanding requirements for higher accuracy. In response, NSK is working to optimize the resolver's lamination geometry, targeting the following improvements:

(1) The lamination used in the Megatorque Motor resolver is the same as that used in the motor. Since the motor lamination is designed with emphasis placed on increasing the torque, space-harmonics of flux density distribution are not necessarily low. Lamination design with low space-harmonics can reduce accuracy errors.

(2) The compensation mentioned above is positional compensation for an individual rotor tooth, which is subsequently applied to all the remaining rotor teeth. By increasing the number of poles of the stator to decrease accuracy errors among the rotor teeth, when compensation data of one tooth is applied to the remaining teeth, the accuracy after compensation is improved.

Figs. 9 and 10 present data on the positioning accuracy after compensation of both a standard Megatorque Motor (in which the resolver lamination and motor lamination are the same) and a newly developed resolver that incorporates the improvements described above.

Accuracy of ±5 seconds or better is achieved by the newly developed resolver.

3.2 Auto-tuning

To get the maximum performance out of DD motors, optimum adjustment, particularly servo-gain adjustment, is necessary. Conventional gain adjustments are mainly carried out manually by users or service representatives. The more widespread use of DD motors has increased the need for easy gain adjustment. In response, NSK developed auto-tuning of DD motors and included it in ESA Driver Units.[6]

3.2.1 Comparison of conventional gain adjustment and auto-tuning

The conventional practice of performing gain adjustment involves the manual setting of the three parameters of position, speed and integration, by determining an optimum combination of them through trial and error. By contrast, in auto-tuning, the driver unit automatically estimates the load inertia and automatically sets up an optimum gain for the inertia. In addition, a test run after the setup of the parameters can be automatically performed. If the result of auto-tuning is not satisfactory, fine adjustment of the auto-tuning is possible. Fig. 11 compares the conventional gain adjusting procedure with the auto-tuning procedure, and Fig. 12 presents test results on them.

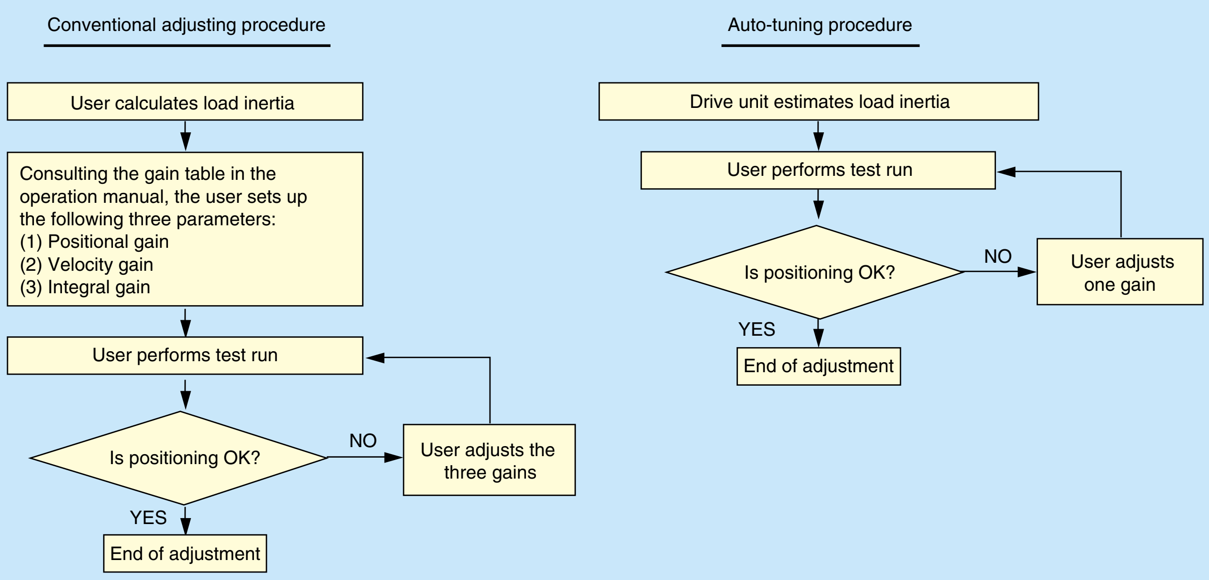


Fig. 11 Conventional and auto-tuning adjustment procedures

Test conditions:

Test motor	Load inertia	Positioning angle	Commanded acceleration/deceleration	Position detection
YS3040	0.223 kgm^2	30°	14.23 rps/s	Within ±10 pulses (21 sec.)

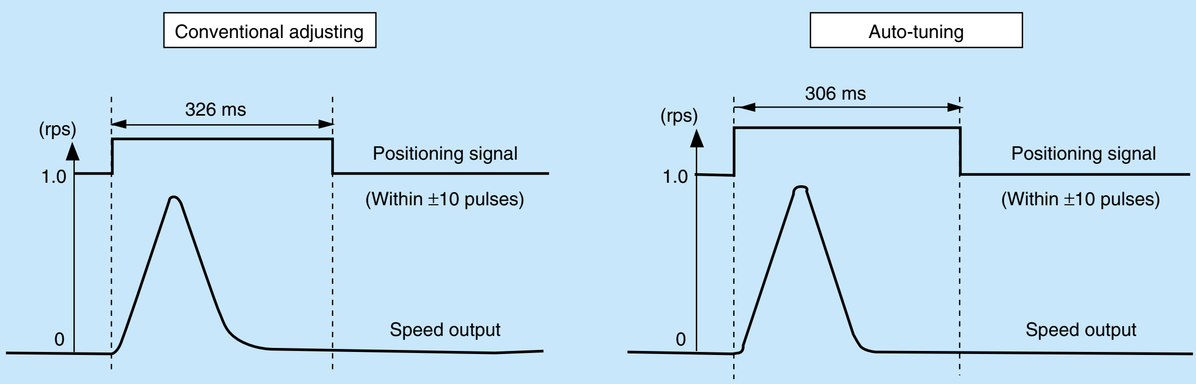


Fig. 12 Results of positioning tests on conventional and auto-tuning procedures

3.2.2 Technical requirements for auto-tuning and NSK's approach to meet the requirements

To ensure good auto-tuning performance, the following two requirements must be met:

(1) Improvement of load inertia estimation accuracy

Various methods are available for the estimation of load inertia. The ESA Driver Unit utilizes an estimation method in which time constants at step inputs are measured, in view of the stability of the inertia at the time of estimation. Considering also the large potential variations in step responses due to the broadness of the permissible range for load inertia in DD motors (the range is approximately equivalent to 1 000 times that of rotor inertia), a method of automatically changing the servo gain when the time constant is measured is used to ensure higher accuracy. As a result, the error of estimated inertia is not higher than ±10%.

(2) Decision of optimum gain for estimated load inertia

For the purpose of deciding optimum gain for estimated inertia, we prepared a model that can perform optimum positioning, free of overshooting when operated with estimated inertia, and can decide position gain, velocity gain, and integral gain for auto-tuning. Auto-tuning has successfully shortened the positioning time of manual tuning by about 20 ms.

Table 1 CE marking directives and NSK countermeasures

Directive	Purpose/Description	NSK's countermeasures
Machinery Directive	To ensure safety of entire mechanical system. For parts used in a system, "declaration of incorporation" may be made.	Because a DD motor is regarded as a part of a system, declaration of conformance is not required for a motor as a single unit. However, NSK ensures conformance of its DD motors, as parts, to European safety standards. NSK declares incorporation. (Issuance of Declaration of Incorporation)
Electromagnetic Compatibility (EMC) Directive	To ensure compatibility between electric and magnetic performance.	EMC must be assured for a system as a whole. On request from users, NSK has its DD motors tested as single units by a competent body for their EMC, and provides users with test results.
Low Voltage Directive	To prevent accidents including electrocutions and fires. Declaration of conformance and CE marking are required even for parts.	Based on advice from a European competent body, NSK conforms to the European safety regulations and voluntarily provides its products with declarations of conformity. (Issuance of Declaration of Conformance) NSK applies CE marking to its conforming driver units.

4. New Functions Expected for DD Motors

The low price, increased ease of use, compactness and engineering labor-saving utility of the YS series Megatorque Motor and Y series Megathrust Motor described above have contributed to creating new DD motor applications. In some new applications, conventional DD motors are required to have additional functions. Improvement of DD motors to make them fully serviceable in a broader range of applications is one of the important tasks of DD motor technical development.

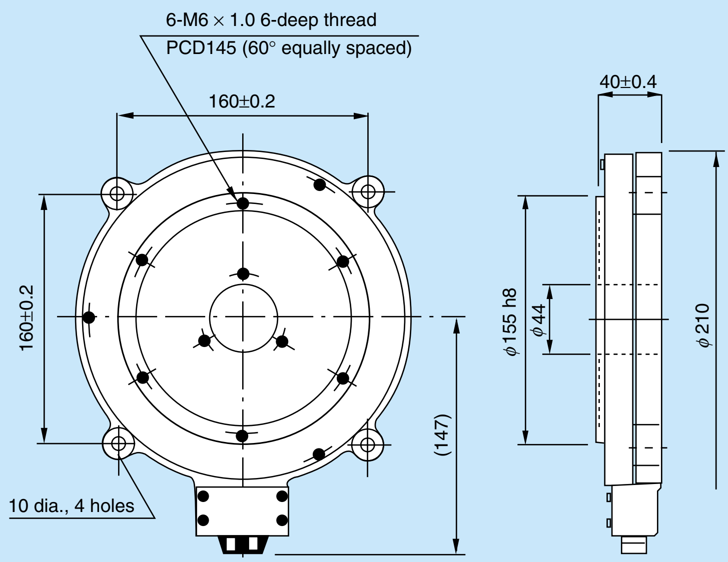
The following sections report on the geometry and construction of new Megatorque Motor series that were developed to conform with increasing CE marking requirements and to satisfy the requirements of a variety of uses.

4.1 CE marking (conforming to European safety standards)

Recently, conformance to CE marking has been increasingly required by domestic users because of the export of their products to Europe. At present, there are three CE marking directives relating to DD motors: the Machinery Directive, the Electromagnetic Compatibility Directive and the Low Voltage Directive. These directives and NSK's countermeasures for them are presented in Table 1. DD motors in the YS series, which includes standard motors, low-profile motors and those equipped with a brake, meet the requirements set down in the CE marking directives.

4.2 Geometry and construction of new series

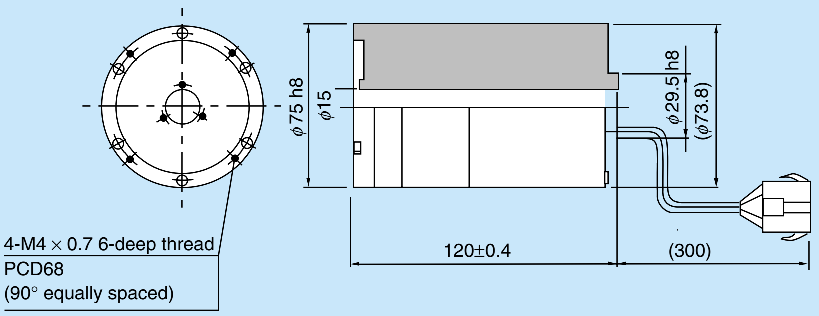
Figs. 13, 14 and 15 present three new series of motors: a low-profile type, a small-size type and a vacuum type. Together these series provide variations in shape and construction to meet the needs of a wide range of applications.



Specifications, features and applications	
Maximum torque	5 – 8 N·m
Maximum speed	3 rps
Positioning resolution	614 400 pulses
Positioning accuracy	±75 seconds
Repeatability	±2.1 seconds

- The thickness of 40 mm permits thin arrangements for theta alignment axis.
- This type of motor, in combination with a Megathrust Motor, was used to create an X-Y table with a theta alignment axis mechanism with an overall height of only 170 mm.

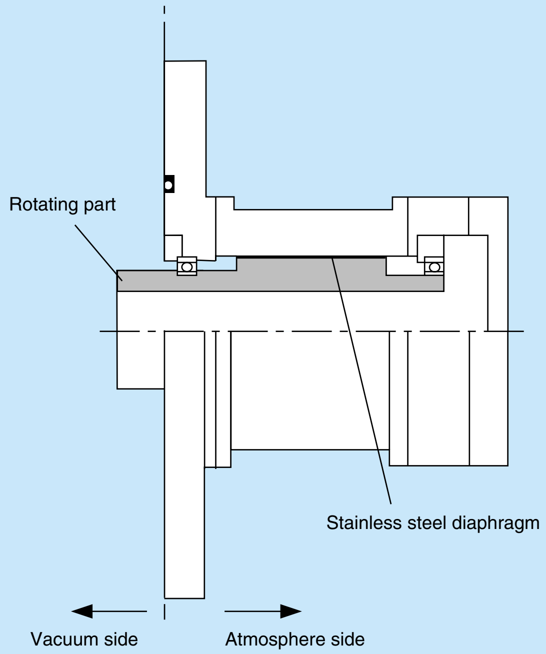
Fig. 13 Low-profile DD motor



Specifications, features, and applications	
Maximum torque	2 – 14 N·m
Maximum speed	3 or 4.5 rps
Positioning resolution	409 600 or 614 400 pulses
Positioning accuracy	±75 or ±150 seconds
Repeatability	±2.1 or ±3.2 seconds

- High-resolution and lightweight motors of small size with a diameter of 75 to 130 mm. Mostly used for theta axis of robots for transferring lightweight loads.

Fig. 14 Small-size DD motor



- No need for magnetic fluid seal
- No need for magnetic coupling
- Serviceable in vacuum of 10^{-7} Pa
- Serviceable at high temperatures up to 120°C

Fig. 15 DD motor for vacuum environments

5. Conclusion

While the range of applications for DD motors, including the Megatorque Motor, has been expanding, so has demand for better performance, more functions and increased ease of use. There are also expectations for new types of DD motors such as highly efficient battery-powered motors for driving the wheels of unmanned transfer carriages and motors with continuous high-speed and high-torque operating accuracy for driving precision grinder tables. At NSK, we will continue working to meet the market requirements for DD motors by further refining and developing our technology.

References:

1) Iwakane, et al, "Japan Robot Association Magazine," 5, 1 (1987) 61
2) Iwakane, "Electronics," E (1988) 28
3) Ishizaki, et al, "Study on Optium Design of PM-type Vernier Motors," Electric Society Reports D, 114-12 (1994)
4) Sawada and Kobayashi, "Control of Direct Drive Motors," NSK Technical Journal, 653 (1992) 42-49
5) Horikoshi, A., "Development of Linear Motors for Wire Bonders," NSK Technical Journal, 659 (1995) 31-37
6) Kobayashi, "Auto-tuning of Direct Drive Motors," NSK Technical Journal, 660 (1995) 47-53
Note: All reference items are in Japanese.


Sadatoshi Kato

New Electronic NSK Product Guide

Yukio Hirata
Bearing Technology Center

1. Introduction

For use with personal computers, NSK has offered its Bearing Pro on floppy disk and CAD data on CD-ROM. Now we have combined technical information and dimension tables from our general catalog on rolling bearings, examples of bearing damage from our Bearing Doctor, and bearing CAD data into one CD-ROM to meet the needs of customers in various industries. In this article, we present a summary of the recently issued NSK Product Guide for bearings (a second CD-ROM for precision products is being prepared and will be released in the near future).

2. Summary of the Electronic Product Guide

2.1 Operating environment

The following operating environment is recommended for the electronic product guide:

CPU: Pentium 166 MHz or faster
OS: Windows 95 with Internet Explorer 3.02
Memory: at least 32 MB
Display: at least 640 × 480 pixels and 256 colors

2.2 Structure of the electronic guide to NSK bearings

When the CD-ROM starts up, the Top display shown in Fig. 1 appears. Clicking on any of the three pictures (Bearings, Overview of Products or Corporate Information) takes the user to that section. To quickly return to this initial display, the user need only click the word Top on the bottom row of each display. Next we describe the three sections: Bearings, Overview of Products, and Corporate Information.

Fig. 1 Top display

2.3 Bearings

When you click the Bearings icon in the Top display, the Main display shown in Fig. 2 will appear. The section on bearings consists of six menus: Bearing ABCs (basic bearing knowledge), Bearing Pro (technical bearing calculations), Bearing Pro Manual, Bearing Doctor (examples of bearing damage), CAD Data, and Dimension Tables.

Fig. 2 Main display in "Bearings"

(1) Bearing ABCs (basic bearing knowledge)

The Bearing ABCs menu allows the technical information in NSK's general catalog on rolling bearings[1)] to be accessed easily and quickly. Information is provided under thirteen headings: Types and Features of Rolling Bearings, Selection of Bearing Arrangement, Selection of Bearing Size, Limiting Speed, Boundary Dimensions and Identifying Bearing Numbers, Bearing Tolerances and Running Accuracy, Fits and Internal Clearances, Preload, Design of Shafts and Housings, Lubrication, Bearing Materials, Bearing Handling, and Running Traces and Applied Loads.

For example, Fig. 3 shows the display for the heading "Types and Features of Rolling Bearings." Clicking any of the 13 types of bearings listed on the left shows the user an illustration of the bearing and provides a brief explanation of its features and characteristics. By clicking "Table of Types and Characteristics of Rolling Bearings" in the lower left, the table shown in Fig. 4 will be shown. This table can be scrolled both horizontally and vertically to quickly compare the characteristics of different types of bearings. Clicking any of the images of the bearings shown on the top row provides the user with a description of the bearing; clicking the same image at the bottom of the table shows dimension tables for the bearing.

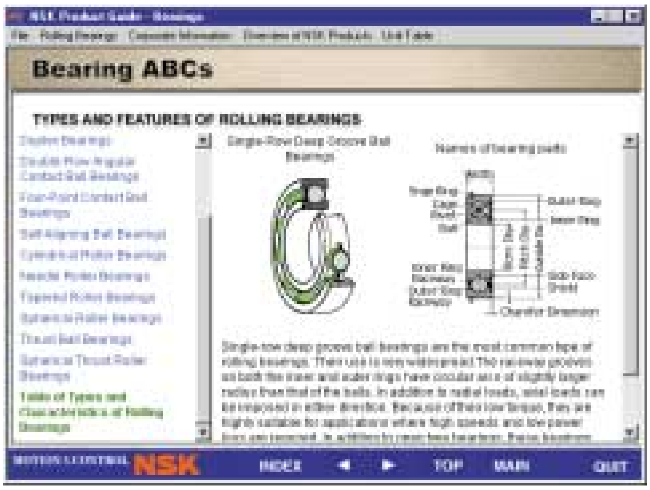


Fig. 3 "Types and Features of Rolling Bearings"

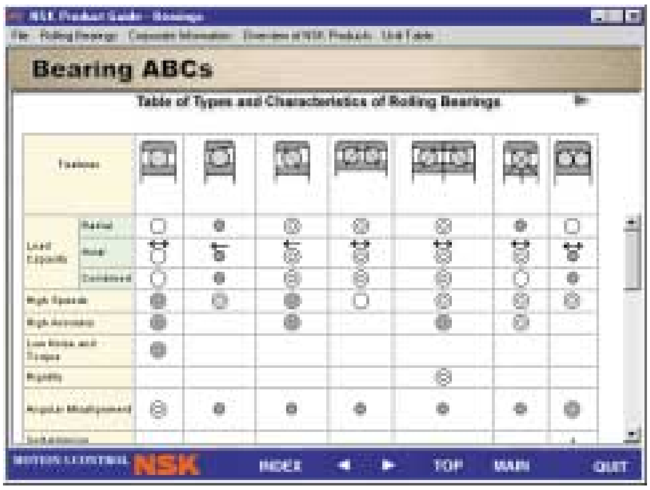


Fig. 4 "Table of Types and Characteristics of Roller Bearings"

(2) Bearing Pro (technical bearing calculations)

In the Bearing Pro section, four technical calculations can be performed: life calculations for individual bearings, life calculations for two bearings supporting a geared shaft and gear load, calculation of fits and clearances, and calculation of bearing frequency vibration ranges. This program can be viewed on the NSK home page at http://www.nsk.com and as mentioned above, has already been made available to customers on floppy disk. Fig. 5 shows the initial display in the Bearing Pro section. By clicking Option on the menu bar and selecting "One Bearing," the life of one bearing can be calculated. Clicking "Two Bearings" allows the user to calculate the load and life of each of two bearings supporting a geared shaft. To facilitate calculation, the user can view the gear system from three perspectives: front, side and isometric. Fig. 6 shows the three perspectives and Fig. 7 the calculation results on the loading conditions of the gears and bearings in a gear system.

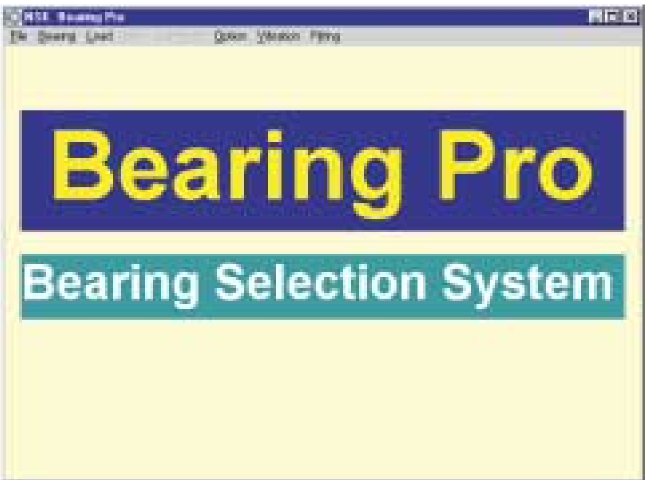


Fig. 5 Initial display in Bearing Pro section

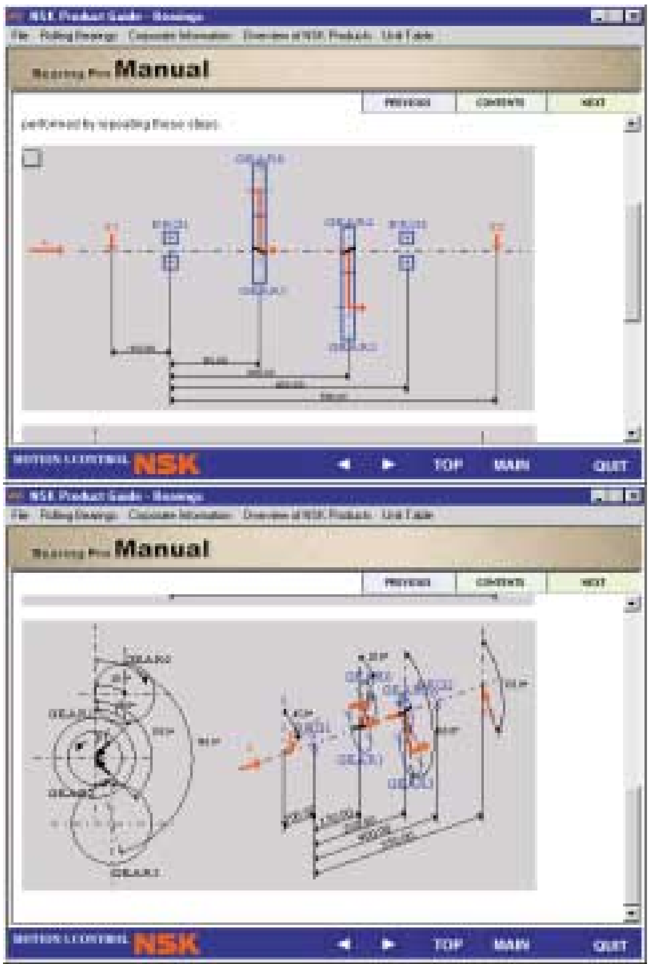


Fig. 6 Front, side and isometric views of bearings on a shaft with spur and helical gears

(3) Bearing Pro Manual

This explains the technical calculation method in the Bearing Pro section. Studying the calculation method by inputting values given in the exercises in the manual will enable the user to perform calculations for even complex cases. We recommend printing out this manual and reading it carefully to perform calculations most efficiently.

(4) Bearing Doctor (examples of bearing damage)

In this section the user can study causes of and countermeasures for 85 instances of 17 kinds of bearing damage including flaking, peeling, scoring, fracture and others. The color images are from NSK's previously

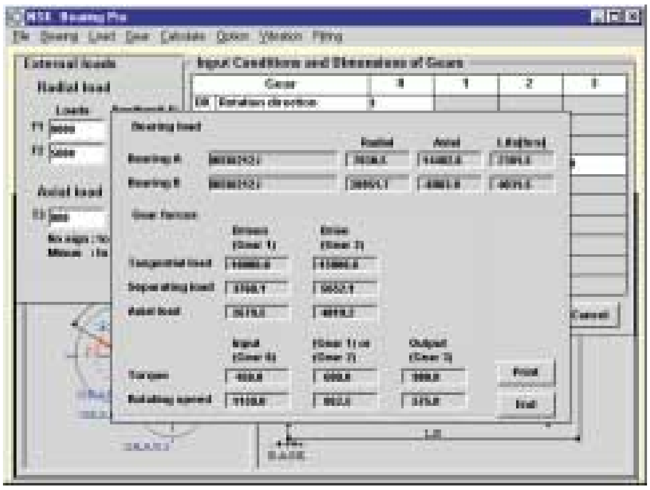


Fig. 7 Calculation results on bearings on a shaft with spur and helical gears

published “New Bearing Doctor.” [2)]

Fig. 8 shows the contents page of the Bearing Doctor section. Clicking any of the pictures shows the user a description of the type of damage, its causes and countermeasures, and photos. Fig. 9a shows the section on flaking. Clicking any of the small photos enlarges it for better viewing (Fig. 9b).

Fig. 8 Contents page in Bearing Doctor section

(5) CAD Data

In the CAD Data section the user can select easily from 5 600 CAD drawings of bearings and housings. Using one of three search methods (boundary dimensions, bearing number or dimension table) the user can find and download drawings of nine types of bearings: deep groove ball bearings, angular contact ball bearings, self-aligning ball bearings, cylindrical roller bearings, tapered roller bearings, spherical roller bearings, thrust bearings, ball bearing units, and plummer blocks.

Fig. 10 shows the display for selecting CAD data on cylindrical roller bearings. The user selects one of the three search methods and then clicks the button for either single-row or double-row cylindrical bearings. Fig. 11 shows the display for determining the desired cylindrical

Fig. 9 a. Information on flaking in Bearing Doctor section
b. Clicking a photo enlarges it

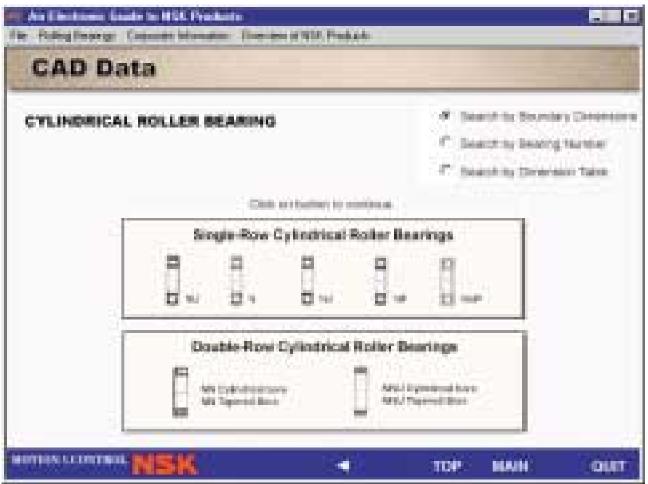


Fig. 10 Display for selecting CAD data on cylindrical roller bearings

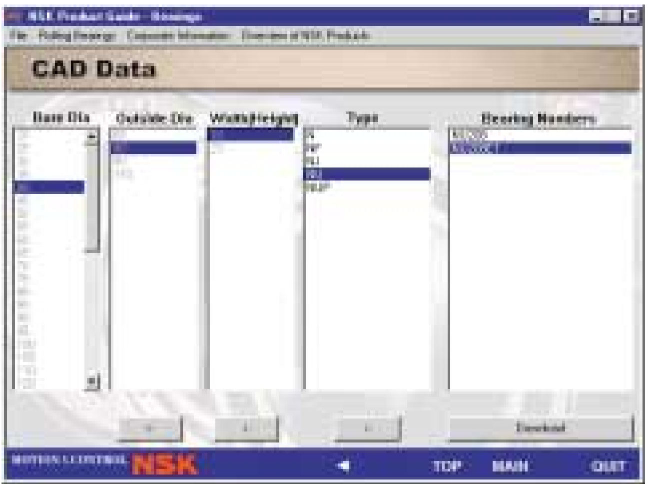


Fig. 11 Determining desired bearing number by bearing dimensions

roller bearing number based on boundary dimensions. After the desired bearing number is determined using the parameters of bore diameter, outside diameter, width (height), and type, the user can download the CAD data.

NOTE: To download and be able to utilize the CAD data in one's personal computer, it is necessary to have DXF software installed beforehand.

(6) Dimension Tables

In the Dimension Tables section, the user can look at the boundary dimensions (bore diameter, outside diameter, width, and chamfer dimension), limiting speed, dynamic load rating, static load rating, abutment and fillet dimensions, mass and other details of 10 types of bearings: deep groove ball bearings, small-diameter miniature ball bearings, angular contact ball bearings, self-aligning ball bearings, cylindrical roller bearings, tapered roller bearings, spherical roller bearings, thrust bearings, ball bearing units and plummer blocks. Fig. 12 shows the dimension table for single-row cylindrical roller bearings as an example.

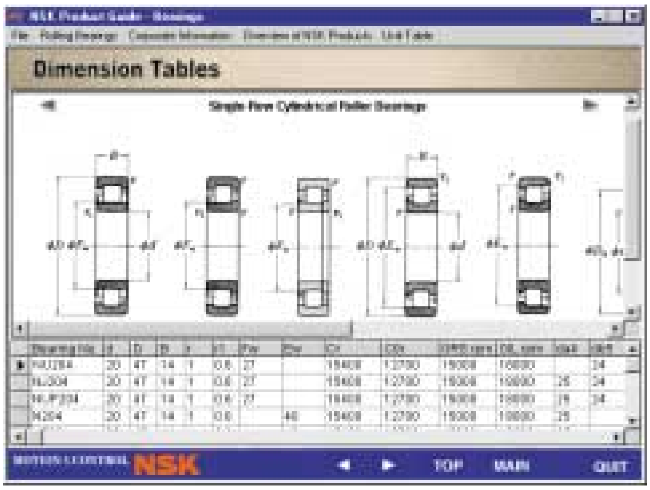


Fig. 12 Dimension table for single-row cylindrical roller bearings

2.4 Overview of Products

Presenting information on bearings, automotive components and precision and electronic products, this section provides an overview of NSK products. Fig. 13 shows part of the segment on automotive products.

2.5 Corporate Information

This section provides basic information on NSK and addresses and telephone numbers for NSK locations around the world.

3. Conclusion

We have presented here NSK's new Product Guide for bearings. It will enable users to learn about the fundamentals of rolling bearings, obtain specific information on bearings, perform life and gear calculations, and access CAD drawings. Considering the

Fig. 13 Automotive products section in "Overview of Products"

opinions and needs of users, we will work to improve this product and make it even easier for customers to use in future editions.

References:

1) NSK Rolling Bearing Catalog, CAT. No. E1101b
2) NSK New Bearing Doctor, CAT. No. E7005

Yukio Hirata

Sound and Vibration in Rolling Bearings

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Basic Technology Research and Development Center

ABSTRACT

Progress in information technology devices and the proliferation of these devices throughout the world have occurred at an astonishingly rapid pace. Not only have there been remarkable improvements in computers, automobiles and electric home appliances, but the total number of such products owned and used by people has increased dramatically.

In the midst of such advancement, demand has grown for rolling bearings with lower vibration and noise. In response, extensive research and development has been undertaken at NSK.

This report summarizes some of the key findings accumulated from research on sound and vibration in bearings, and discusses vibration modes of bearing rings. In addition, a useful table summarizing sound and vibration in bearings is included as a convenient reference tool for the reader.

1. Introduction

Progress in information technology devices has occurred at a dizzying pace and the widespread use of these devices has been truly remarkable. Personal computers are found in businesses and homes throughout the world and it appears that improvements in their performance have no end in sight. At the same time, new software and peripheral devices are appearing on an almost daily basis. As for performance improvement of office automation

Table 1 Classification of sound and vibration in rolling bearings

	Sound		Vibration		Features
Structural	Race noise		Free vibration of raceway ring		Continuous noise, basic unavoidable noise which all bearings generate
	Click noise		Free vibration of raceway ring, free vibration of cage		Regular noise at a certain interval, large bearings and horizontal shaft, radial load and low rpm
	Squeal noise		Free vibration of raceway ring		Intermittent or continuous, mostly large cylindrical roller bearings, radial load, grease lubrication, at particular speed
	Cage noise	"CK" noise	Free vibration of cage		Regular noise at a certain interval, all bearing types generate it
		"CG" noise	Vibration of cage		Intermittent or continuous, lubrication with particular grease
		Tapping noise	Free vibration of cage		Certain interval, but a little irregular under radial load and during initial stage
	—		Rolling element passage vibration		Continuous, all bearing types under radial load
Manufacturing	Waviness noise		Vibration due to waviness	Inner ring	Continuous noise
				Outer ring	Continuous noise
				Rolling element	Continuous with rollers, occasional with balls
Handling	Flaw noise		Vibration due to flaw	Inner ring	Regular noise at a certain interval
				Outer ring	
				Rolling element	
	Contamination noise		Vibration due to contamination		Irregular
Others	Seal noise		Free vibration of seal		Contact seal
	Lubricant noise		—		Irregular
	—		Runout	f_r	Continuous
				f_c	Continuous
				$f_r - 2f_c$	Continuous

equipment, particularly personal computers and related products, demand is high for ever-lower vibration and sound levels of moving components. In the automotive and home appliance industries, performance improvement continues unabated and the average number of such products owned by households increases steadily. For consumer goods such as air conditioners, washing machines, refrigerators, vacuum cleaners and automobiles, quietness is a key selling point that often helps clinch sales.

Amid these market conditions, requirements for low vibration and sound in rolling bearings become more severe every year. At NSK, intensive R&D is being undertaken to meet such requirements, particularly for small and ultra-small ball bearings. For example, results of research on low vibration and low noise in VCR bearings served as the foundation for NSK's recently developed HDD bearings, which are acclaimed for their world-class quality. In this report, we discuss vibration and sound in rolling bearings based on key findings from past research.

2. Classification of Vibration and Sound in Bearings

The various types of vibration and sound in rolling bearings are grouped into the four categories listed in Table 1.[1)] While other ways of classifying vibration and sound exist, the discussion in this report is based on the classification system in this table. In this classification system, the distinctions between the categories are not absolute. For example, the magnitude of structural sound or vibration is partially related to the manufacturing process. When sound is generated, in most cases vibration occurs, and when vibration occurs, usually sound is generated. For example, when vibration is caused by waviness, it is assumed that at the same time a "waviness sound" is generated. While vibration and sound almost always accompany each other, problems of vibration and sound are usually characterized in terms of one or the other. This is because the ability or inability of humans to hear sound or sense vibration depends on frequency. Low-frequency sound is barely audible while high-frequency vibration cannot be perceived by humans. For this reason, problems at low frequency are "vibration problems," and

Table 1 (continued)

Generated frequency (frequency analysis)			Source	Countermeasures
FFT of original wave		FFT after envelope (basic No.)		
Radial (angular) direction	Axial direction			
f_{RiN}, f_{M1}	f_{AiN}, f_{AM}	—	Selective resonance of waviness (rolling friction)	Improve rigidity around the bearings, appropriate radial clearance, high-viscosity lubricant, high-quality bearings
f_{RiN}, f_{M1} Natural frequency of cage	f_{AiN}, f_{AM}	Zf_c	Collision of rolling elements with inner ring or cage	Reduce radial clearance, apply preload, high-viscosity oil
($\approx f_{R2N}$, f_{R3N})	—	?	Self-induced vibration caused by sliding friction at rolling surface	Reduce radial clearance, apply preload, change the grease, replace with countermeasured bearings
Natural frequency of cage		f_c	Collision of cage with rolling elements or rings	Apply preload, high-viscosity lubricant, reduce mounting error
Natural frequency of cage		?	Self-induced vibration caused by friction at cage guide surface	Change the grease brand, replace with countermeasured cage
Natural frequency of cage		Zf_c	Collision of cage and rolling element caused by grease resistance	Reduce radial clearance, apply preload, low-viscosity lubricant
Zf_c	—	—	Displacement of inner ring due to rolling element passage	Reduce radial clearance, apply preload
$nZf_i \pm f_r$ ($nZ \pm$ 1 peaks)	nZf_i (nZ peaks)	—	Inner ring raceway waviness, irregularity of shaft exterior	High-quality bearings, improve shaft accuracy
nZf_c ($nZ \pm$ 1 peaks)	nZ_{fc} (nZ peaks)	—	Outer ring raceway waviness, irregular bore of housing	High-quality bearings, improve housing bore accuracy
$2nf_b \pm f_c$ ($2n$ peaks)	$2nf_b$ ($2n$ peaks)	—	Rolling element waviness	High-quality bearings
f_{RiN}, f_{M1}	f_{AiN}, f_{AM}	Zf_i	Nicks, dents, rust, flaking on inner ring raceway	Replacement and careful bearing handling
		Zf_c	Nicks, dents, rust, flaking on outer ring raceway	Replacement and careful bearing handling
		$2f_b$	Nicks, dents, rust, flaking on rolling elements	Replacement and careful bearing handling
f_{RiN}, f_{M1}	f_{AiN}, f_{AM}	Irregular	Entry of dirt and debris	Washing, improve sealing
Natural frequency of seal		(f_r)	Self-induced vibration due to friction at seal contact area	Change the seal, change the grease
?	?	Irregular	Lubricant or lubricant bubbles crushed between rolling elements and raceways	Change the grease
f_r	—	—	Irregular inner ring cross-section	High-quality bearings
f_c	—	—	Ball variation in bearing, rolling elements non-equidistant	High-quality bearings
$f_r - 2f_c$	—	—	Non-linear vibration due to rigid variation by ball variation	High-quality bearings

n: Positive integer (1, 2, 3...)
Z: Number of rolling elements
f_{RiN}: Ring natural frequency in radial bending mode, Hz
f_{M1}: Natural frequency in the mode of angular vibration in inertia of outer ring-spring system, Hz
f_r: Rotation frequency of inner ring, Hz
f_c: Orbital revolution frequency of rolling elements, Hz
f_{AiN}: Ring natural frequency in axial bending mode, Hz
f_{AM}: Natural frequency in the mode of axial vibration in mass of outer ring-spring system, Hz
f_i: $f_i = f_r - f_c$, Hz
f_b: Rotation frequency of rolling element around its center, Hz

those at high frequency are "noise problems." As a rule of thumb, the arbitrary border separating vibration problems from noise problems is 1 000 Hz. In other words, below 1 000 Hz is considered to be vibration and above 1 000 Hz is sound or noise.

3. Types of Vibration and Sound in Bearings

3.1 Structural vibration and sound

Even when the most advanced manufacturing technology is used, vibration and sound still occur naturally in rolling bearings. As such vibration and sound do not degrade bearing performance, they are accepted as normal bearing characteristics.

3.1.1 Race noise

Race noise is the most basic sound in rolling bearings. It is generated in all bearings and is a smooth and continuous sound. At NSK we say it sounds like "sha-ahh." The magnitude of this sound is used to assess bearing quality. Fig. 1 shows how the magnitude of race noise compares to familiar sounds.[2] In this figure, even the sound generated by the loudest of the bearings, bearing #6410, is only about 1/100 of the magnitude of normal conversation. It is clear that the energy associated with race noise is very limited. The characteristics of race noise are as follows:[3]

(1) The frequency of the sound does not change even when rotational speed changes. Its frequency is the natural frequency of the raceway rings, as illustrated in Fig. 2.
(2) The faster the running speed, the louder the sound.
(3) If radial clearance is reduced, the sound becomes louder.
(4) As for the lubricant, when its viscosity is higher the sound is reduced. Besides the viscosity of the grease, the consistency, form and size of the soap fiber in it also affect noise performance.
(5) The higher the rigidity of the housing, the lower the magnitude of the sound.

Race noise is considered to be caused by configuration error (called microundulation or waviness), which occurs even when the most advanced machining technology is used to process the surfaces of the raceways and rolling elements of a bearing. Due to this waviness, the contact between the raceway rings and rolling elements behaves like a spring that fluctuates minutely during bearing operation. The variation of this so-called spring acts as an excitation force on the raceway rings of the bearing. Consequently, vibration and race noise are generated.

The generation of race noise is inevitable and there are no special countermeasures to eliminate it completely. However, it can be minimized by improving the overall quality and precision of bearings.

3.1.2 Click noise

Click noise tends to occur more often in relatively large bearings under radial loads. It is generated only at low speeds, disappearing when speed exceeds a certain level. A rough approximation of this noise used at NSK is "kata kata." It is somewhat similar to flaw noise, which is described in a following section. The generation of click noise is believed to proceed as follows (Fig. 3). When a bearing is operated under a radial load, then a load zone and no-load zone exist inside the bearing. The bearing has some clearance in the no-load zone—rolling elements do not touch the inner ring, but do touch the outer ring due to centrifugal force (F_{c2}). However, at low speeds, when centrifugal force becomes less than the force of gravity (W_1), the rolling elements fall and collide with the cage and/or inner ring. It is the collisions between the rolling

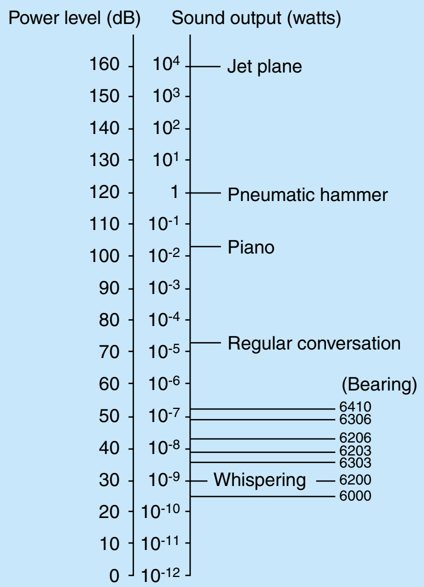

Fig. 1 Loudness range of race noise

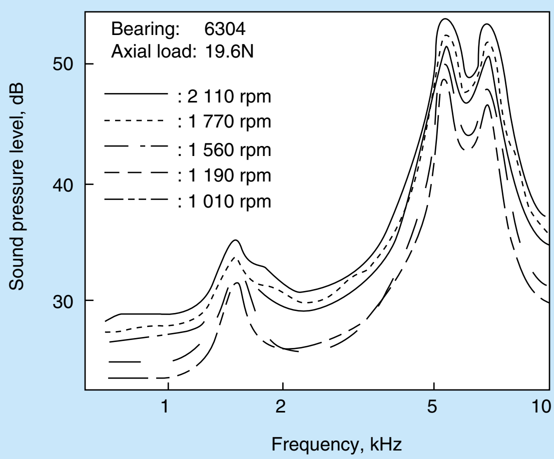

Fig. 2 Influence of rotation speed on race noise

elements and the cage and/or inner ring that generate click noise.

Applying a preload is an effective countermeasure to click noise. Reducing radial clearance results in only a small improvement. Another remedy is using light rolling elements like those made of ceramic.

3.1.3 Squeal noise

Squeal noise is a metallic noise that can be rather loud in some cases. It sounds like metal sliding on metal and we express it in Japanese as "kyuru kyuru." With squeal noise, bearing temperature does not generally rise and bearing and grease life are not adversely affected. In fact, beyond the noise problem (if indeed it is actually a problem), there is no other hindrance to bearing operation. Squeal noise tends to occur with relatively large bearings used under a radial load. It occurs frequently in cylindrical roller bearings, but may also occur in ball bearings. The characteristics of squeal noise are:

(1) It tends to occur when radial clearance is large.
(2) It occurs mostly with grease lubrication and only rarely with oil lubrication.
(3) It occurs more often in winter.
(4) It occurs within a certain speed range that tends to become lower as bearing size increases.
(5) Its generation is inconsistent and unpredictable, and depends on the kind and amount of grease, as well as bearing operating conditions.

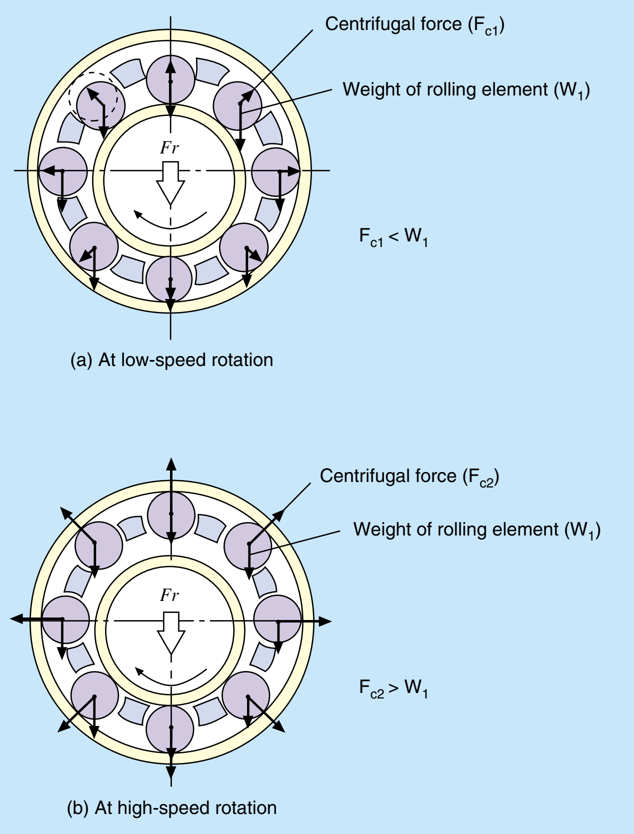

Fig. 3 Mechanism of rolling element falling noise

Influenced by the lubrication used and increasing vibration of the outer ring, the friction between the outer ring and rolling elements is considered to be the cause of squeal noise. Squeal noise is attributed to self-induced vibration related to lubrication. However, there is an important question: From what part of the circumference of the outer ring is squeal noise emitted? The jury is still out on this question as some experts believe the noise is generated in the load zone while others argue that it is generated in the no-load zone.[4),5)] Effective countermeasures to squeal noise include reducing the radial clearance and employing a very shallow groove in the outer ring raceway of the bearing.[6)]

3.1.4 Cage noise

There are two kinds of cage noise: a noise suggestive of the cage colliding with rolling elements or bearing rings ("kacha-kacha" at NSK) and a low-frequency noise ("gaga gaga"). NSK differentiates them by calling them "CK noise" and "CG noise," respectively. CK noise can be generated in any type of bearing and the magnitude of it is usually not very high. Characteristics of this noise include:

(1) It occurs with pressed steel cages, machined cages and plastic cages.
(2) It occurs with grease and oil lubrication.
(3) It tends to occur if a moment load is applied to the outer ring of a bearing.
(4) It tends to occur more often with greater radial clearance.

CK noise is attributed to the rotating cage colliding with rolling elements or raceway rings. As there is clearance between the cage and both the rolling elements and raceway rings, it is difficult to completely eliminate CK noise. However, it can be reduced to some extent by reducing the mounting error.

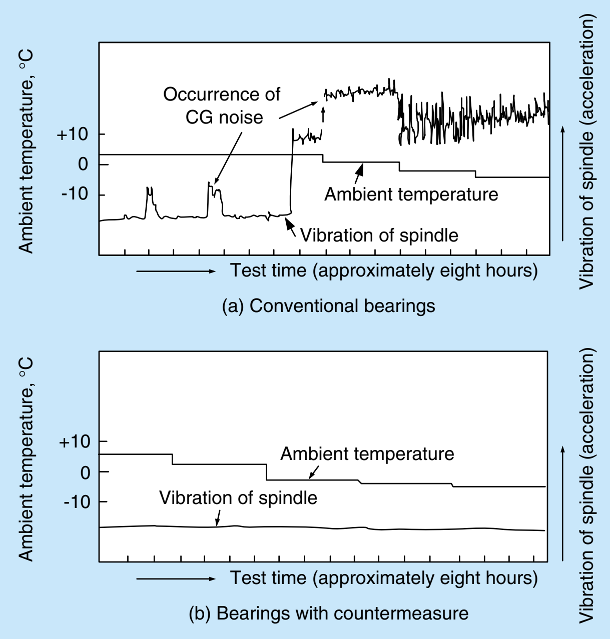

Fig. 4 Performance evaluation test of cage noise (CG noise)

CG noise is a special noise which, in Japan, is perceived as being similar to a croaking frog. It is attributed to self-induced vibration of the cage caused by sliding friction between the cage guide face and the bearing component that guides the cage. It frequently becomes loud and therefore problematic. For this reason, a bearing was specially designed with the expressed purpose of suppressing cage noise of this type.[7] Fig. 4 compares the performance of a conventional bearing, to which no countermeasure was applied, to a bearing with a specially designed cage. The bearings were mounted on a spindle, and because CG noise tends to occur at lower temperatures, ambient temperature was gradually lowered during the test. In the bearing with the specially designed cage, cage noise did not occur even after the ambient temperature went below 0°C. CG noise is generated with grease lubrication and tends to occur with relatively hard grease. The use of the specially designed cage is effective in reducing CG noise, as is the careful selection of lubricant.

When a bearing is used under a radial load with hard grease, a loud cage noise (sounding roughly like "gacha gacha") may occur at the initial stage of rotation. This noise is caused by the rolling elements colliding with the cage as they suddenly decelerate due to grease resistance after departing the load zone. However, this noise becomes negligible and eventually disappears with time.

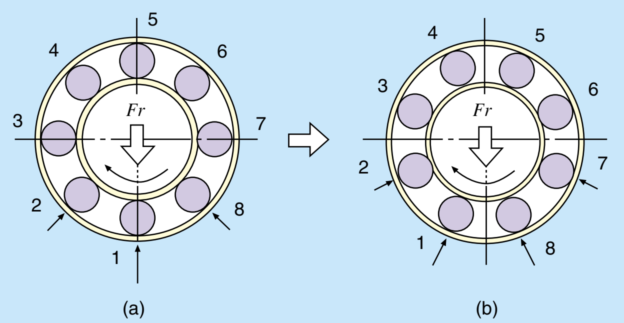

Fig. 5 Mechanism of vibration due to rolling elements passing

3.1.5 Rolling element passage vibration

Rolling element passage vibration becomes a problem mostly in rolling bearings operating under a radial load. When this kind of vibration occurs, the shaft's center of rotation runs out both vertically and horizontally and a noise, which at NSK is expressed as "goro goro," may occur. The amplitude of this vibration is influenced by radial clearance, radial load and the number of rolling elements. This type of vibration occurs due to variation in load sharing that depends both on the position of each rolling element in the load zone and on the minute variation in the amount and direction to which the shaft is displaced. Comparing conditions (a) and (b) in Fig. 5, the displacement of the rotating shaft in the vertical direction is slightly different. The shaft also moves transversely between the conditions shown in the figure. Theoretical and experimental studies indicate that the frequency of this vibration can be expressed as:[8]

$$f = Z \cdot f_c \ (Hz)$$

Z: Number of rolling elements
f_c: Orbital revolution frequency of rolling elements (Hz)

As rolling element passage vibration is usually of small amplitude, it rarely becomes a problem. When it does become a problem, reduction of radial clearance or application of a preload can be effective countermeasures.

3.2 Vibration and sound related to bearing manufacturing

Vibration and sound related to bearing manufacturing, the most significant type of which is caused by waviness, cannot be eliminated completely. Even with modern

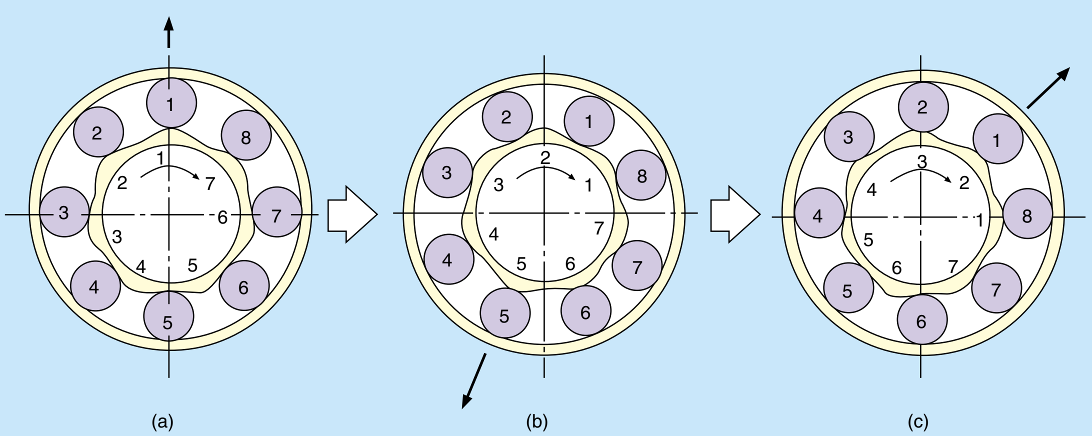

Fig. 6 Mechanism of vibration due to waviness of raceway or rolling element surface

precision machining technology, an element of waviness exists that will generate sound and vibration albeit, however, at negligible levels. It is only when waviness is abnormal (due either to factors relating to manufacturing or a particular bearing's application) that waviness noise becomes a problem. Unlike most other sounds generated by rolling bearings, the frequency of waviness noise depends on the speed. This is an important characteristic by which waviness noise can be distinguished from other types of noise. At a constant rotational speed, waviness noise is harsh and has a constant frequency. At NSK we say it sounds like "ooh ooh" or "whan whan." When a bearing is accelerating or decelerating, waviness noise is even more harsh and its frequency increases or decreases with speed. NSK's approximation of this noise is "hee-yun." Waviness noise becomes a problem when the vibration caused by the waviness of the raceways and/or rolling elements is excessive.

Gustafsson conducted a basic study on vibration caused by waviness.[9] He considered waviness in the circumferential direction on the surface of the inner and outer ring raceways and rolling elements as a group of sinusoidal waves. He examined the force balance inside the bearing when such waviness exists and calculated the bearing vibration caused by it. As a result, he determined the number of waviness peaks that cause vibration and the frequency of this vibration. The section of Table 1 regarding the frequency of waviness noise reflects these findings. As it is clear from Table 1, waviness with a specific number of peaks is the cause of this vibration. As is shown in Fig. 6, vibration in the radial direction occurs when waviness with (*nZ-1*) peaks exists on the inner ring.

Gustafsson's analysis of vibration was based on a constant axial load being applied and only one component having waviness. Since his research, others have analyzed cases where waviness existed on two components and radial load was applied.[10), 11)] According to these studies, vibration occurs with additional numbers of waviness peaks. While the generation of vibration and noise with the number of peaks deduced by Gustafsson and shown in Table 1 has been confirmed in numerous cases, not enough experimental data have been gathered to confirm the additional numbers of peaks in the more recent research.

To avoid problems, this vibration (waviness noise) can be reduced by decreasing the waviness in the circumferential direction on the finished surfaces of the bearing components. Additionally, it should be noted that if waviness exists on the fitting face of the shaft or housing to which the bearing is mounted, then this waviness reflects onto the raceway surface of the bearing and generates vibration. If a spline is cut on the shaft, a similar effect may result. Therefore, careful attention is required.

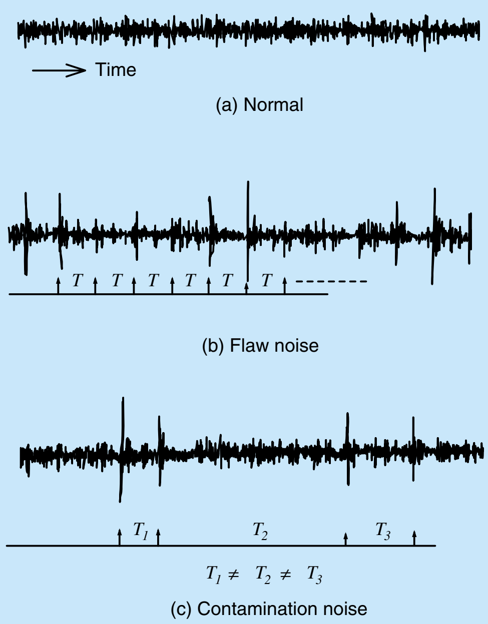

Fig. 7 Waveform of noise due to flaw and contamination

3.3 Vibration and sound due to improper handling

Major components of a bearing have a harder surface than HRC60, so they are usually tough. But if a bearing is dropped or otherwise sustains a shock, dents can result on the finished surfaces of the bearing components. Even a slight defect in shape may cause vibration or sound. In addition to dents and flaws, minute contamination may cause problems. Vibration and sound in this group are mainly caused by improper handling of the bearing.

3.3.1 Flaw noise

When a flaw such as a dent or rust exists on a finished raceway surface of a rolling bearing, then a pulsating, machine-gun-like noise is generated when the bearing rotates. At NSK this noise is expressed as "beee." It is caused by the rolling elements hitting the flaw on the raceway surface and is called flaw noise. As Table 1 shows, its frequency is the same as that of race noise. When flaw noise is generated, the level of the entire frequency spectrum rises. As a result, analyzing the frequency simply by FFT is not sufficient to distinguish it from some other noises. Flaw noise has unique generation cycles or intervals when compared to other types of noise (Fig. 7). At a constant speed, the noise generation cycle is constant, but as the speed decreases, the noise generation cycle becomes longer. This cycle is determined by speed and the internal specifications of the bearing. As Table 1 shows, it also changes with the position of the flaw on the bearing.[12)] Due to this characteristic, it is possible to determine whether flaws exist and if so, where they are located. To determine the generation cycle of such a noise, a method called envelope analysis is used.

In the case of a ball bearing with a flaw on a ball, but not necessarily on the rolling surface of the ball, noise due to the flaw sometimes occurs and sometimes does not. When such noise is generated, it will always have a cyclic characteristic.

When grease of high viscosity is used, the noise is masked and the level of the noise tends to be reduced.

However, when noise due to a flaw on a rolling element occurs, usually the bearing should be replaced.

3.3.2 Contamination noise

The ingress of foreign particles into a bearing, either from improper handling or severe operating conditions, results in contamination noise, which at NSK is approximated by “chi chi chi.” It results from foreign particles being caught between the rolling elements and raceway surfaces. The magnitude of contamination noise is not constant and its generation is irregular (Fig. 7). Generally, the smaller the bearing, the larger the influence of foreign particles. Contamination noise frequently is a problem with small-size or extra-small-size bearings. The entry of foreign particles not only causes noise but can also cause dents on the rolling surfaces of the bearing and thereby shorten bearing life. For this reason, preventive measures must be taken.

3.4 Other vibration and sound

The various types of sound and vibration in Table 1 that have been described to this point are fairly well understood. However, the types of sound and vibration in the category titled “Others” are not as well understood. The first of these is seal noise. In a grease-lubricated bearing with contact seals, a “peee” noise may occur. This noise is attributed to self-induced vibration caused by friction between the seals and seal contact points. As a countermeasure, a different kind of seal or grease can be adopted.

During the initial rotation of a bearing with grease lubrication, noises that are roughly equivalent to “pee-shee” or “jyuu” may be heard. These noises are believed to be generated when lubricant or lubricant bubbles are crushed between the rolling elements and raceways. Their generation is irregular and ceases as running time elapses. This type of noise is not considered to be a significant problem as its magnitude is low.

Next we discuss three types of vibration in rolling bearings: the f_r, f_c and f_r-$2f_c$ vibration components. The f_r component is runout that is caused by an unbalanced shaft or uneven thickness of the inner ring. The frequency of this vibration is the same as the rotation frequency. The f_c component occurs if there is a difference in the diameters of the rolling elements or if the arrangement of the rolling elements is not equidistant. The frequency of this component is the same as the orbital revolution frequency of the rolling elements.[13] The f_r-$2f_c$ component occurs when a difference in the diameters of the rolling elements affects the spring characteristics of the shaft and bearing. It has been pointed out that this directional characteristic rotates at f_c, and the frequency of this vibration is the f_r-$2f_c$ frequency.[13] For all of these vibration components, similar to vibration caused by waviness, the frequency varies as rotational speed changes. Waviness, f_c and f_r-$2f_c$ vibration all are components of non-repetitive runout (NRRO) and as such are important topics in HDD research and development.

4. Frequency of Vibration and Sound in Bearings

4.1 Natural frequency of raceway rings

As can be understood from Table 1, many frequencies of vibration and sound generated in bearings are related to the natural frequency of the raceway rings. Of the two raceway rings, the natural frequency of the outer ring becomes a problem more often than the inner ring due to a loose fit between it and the housing. The modes of vibration of the outer ring are roughly divided into two categories: those that consider the outer ring as a rigid body and those that consider it as an elastic body.[3] Besides these, there are modes of vibration associated with each bearing component such as the cage. However, these vibrations have not been systematically studied yet due to the complexity of the modes of vibration and the number of factors involved including shape, material and other variables.

4.1.1 Rigid body modes

For a rigid body, there are two modes of vibration which, for the sake of clarity, we will call mode A and mode B. Mode A is angular vibration in the inertia outer ring-spring system, and mode B is vibration in the mass outer

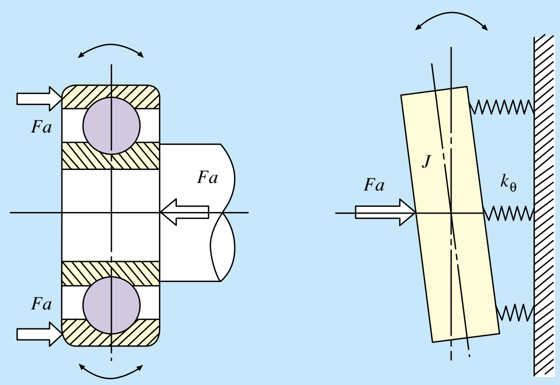

Fig. 8 Mode of angular vibration in inertia of outer ring-spring system

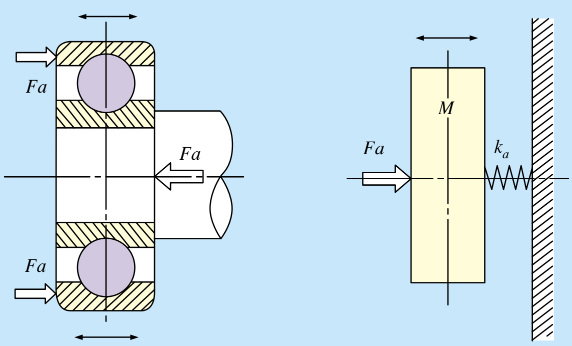

Fig. 9 Mode of axial vibration in mass of outer ring-spring system

ring-spring system. Mode A is illustrated in Fig. 8. Mode B can be divided further into radial and axial vibration, but because radial vibration rarely becomes a problem, only the mode of axial vibration is analyzed. So, mode B is the vibration in the system of the mass of the outer ring and spring in the axial direction of the bearing. It is illustrated in Fig. 9. To find the natural frequency, one needs to determine the spring coefficient of a bearing, which takes a long time. Fortunately, for ball bearings to which a pure axial load is applied, there is a formula which allows natural frequency to be calculated easily.[14)]

4.1.2 Elastic body modes

An example of a vibration mode in which the outer raceway ring is considered as an elastic body is the bending mode. This vibration mode is divided into radial and axial modes, as shown in Fig. 10. In these vibration modes, the outer ring becomes a problem more frequently. There are several formulas for calculating the natural frequency of the bending mode in the outer ring of a ball bearing.[15), 16), 17)] These formulas give the value of the natural frequency when a bearing is free, which for most applications is sufficiently accurate. When higher degrees of accuracy are required, a more complicated method of calculation that takes into account mounting conditions must be used.

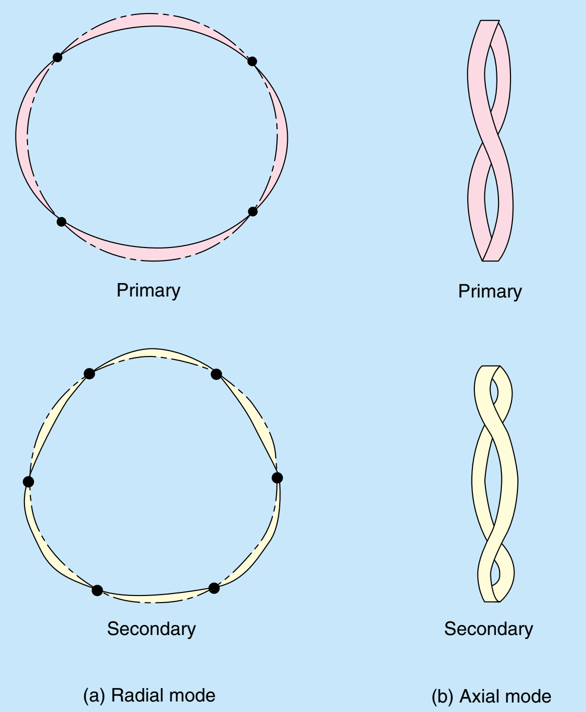

Fig. 10 Mode shapes for bearing rings (bending mode)

4.2 Rotation frequency of rolling elements

As is apparent from Table 1, in order to calculate either the frequency of vibration caused by waviness or the envelope frequency of flaw noise, the orbital revolution frequency of the rolling elements (f_c) and the rolling element frequency (f_b) are required. These values are determined by the internal specifications of a bearing and the running speed. They can be calculated with the following formulas:[3)]

$$f_c = \frac{1}{60} \cdot \frac{n_i}{2} \left(\frac{d_m - D_a \cdot \cos\alpha}{d_m} \right)$$

$$f_b = \frac{1}{60} \cdot \frac{-n_i}{2} \left(\frac{d_m}{D_a} - \frac{D_a \cdot \cos^2\alpha}{d_m} \right)$$

f_c: Orbital revolution frequency of rolling elements (Hz)
f_b: Rotation frequency of rolling elements (Hz)
n_i: Running speed of inner ring (rpm)
D_a: Diameter of rolling elements (mm)
d_m: PCD of rolling elements (mm)
a: Contact angle (°)

5. Conclusion

We have presented here a summary of the types of vibration and sound in rolling bearings. Among the different kinds of sound and vibration in Table 1, most of them are fairly well understood and the countermeasures explained in this report can be employed to control them when they are deemed excessive. There are still, however, some that are as yet not completely understood. Research is ongoing at NSK in these areas. In any case, it should be understood that, due to the fundamental nature of rolling bearings and limitations on machining technology, a certain degree of vibration and sound is unavoidable.

Vibration and sound generated by rolling bearings is relatively low compared to other machine components. Nevertheless, some customers still request reduced noise. This indicates the pivotal role bearings play in controlling noise generated by machines and probably stems from the fact that sound and vibration can be transmitted from bearings to other parts of a machine and amplified there. For this reason, continued research, not only on bearings, but on their surrounding structures as well, is required.

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* In Japanese

Tatsunobu Momono

Banda Noda

Lightweight, Low-Cost TKZ Clutch Release Bearings

NSK has recently developed lightweight and low-cost TKZ self-centering clutch release bearings with resin sleeves (Fig. 1). The mass-production of these bearings began in autumn 1998. Without compromising performance or quality, we have been able to drastically reduce the price and weight of these new bearings.

Half the weight and much more economical than existing clutch release bearings with resin sleeves, TKZ bearings can be used in new designs and as replacements for the existing five types of NSK clutch release bearings. The existing five types are:

TKA: Plastic ring method with iron sleeve
TKB: Spring method with resin sleeve
TKT: Spring method with resin sleeve
TKE: Spring method with iron sleeve
TKC: Spring method with separated sleeve

Features

■ Long life
Durability exceeds two million clutch release strokes (equivalent to 200 000 km)

■ Low torque
Resulting from light-contact seals

■ Low noise
Less than 55 dB when new

■ No lubrication necessary between sleeve and shaft
As wear of even aluminum shafts is eliminated by the new NSK-developed resin sleeve, no lubricant is required between the sleeve and shaft.

	Contact diameter	Bore	Assembled width
Small-size cars	ϕ44	ϕ28	20
Medium-size cars	ϕ50	ϕ33	22
SUVs	ϕ54	ϕ36	24

Available Sizes

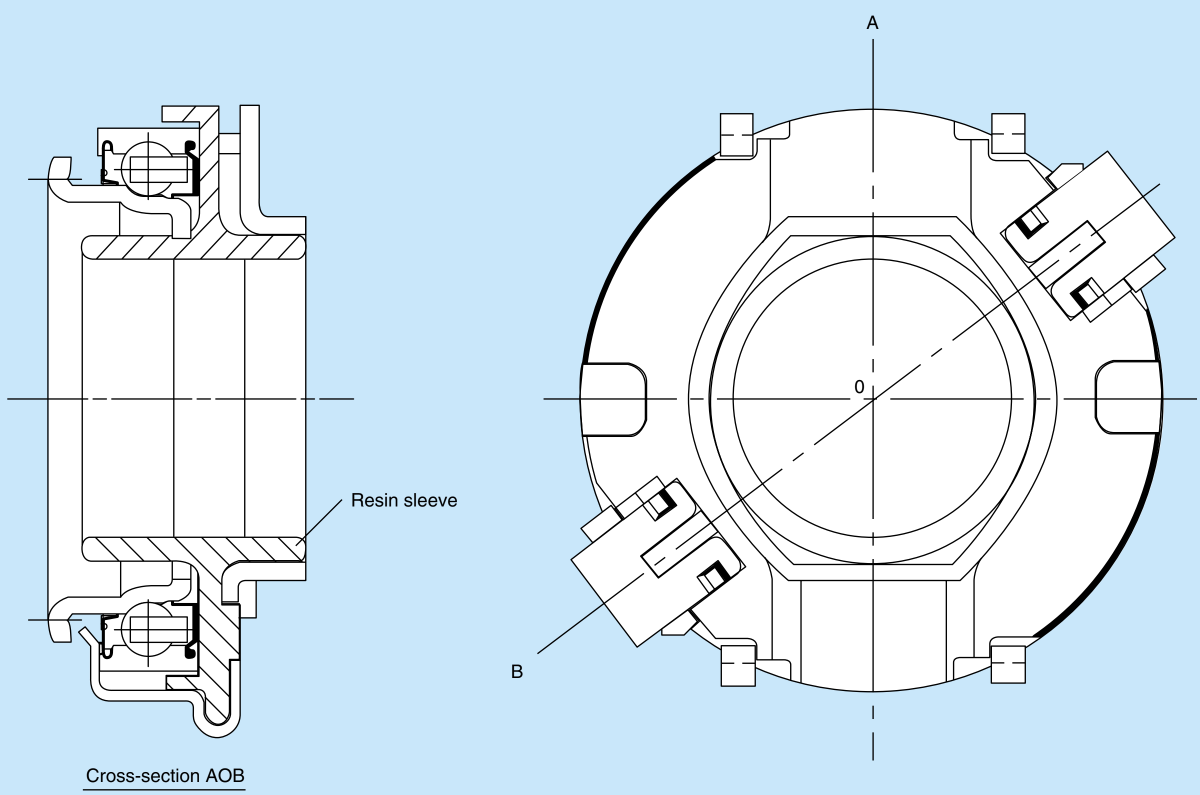

Fig. 1 TKZ clutch release bearing

Cam-In Bearings™— Bearings with Built-In One-Way Clutches

Conventional washing machines generally use two standard deep groove ball bearings and a one-way (roller) clutch, as shown in Fig. 1. Recently, compact components are required in order to free more space for higher-capacity washing tanks. To meet this requirement, NSK has developed Cam-In Bearings™, compact and quiet bearings with built-in one-way clutches.

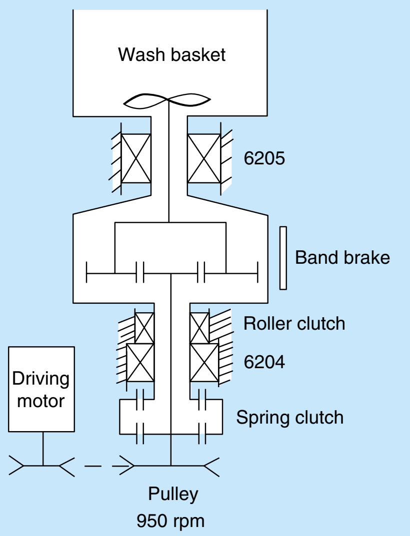

Fig. 1 Interior structure of conventional washing machine


Photo 1 Cam-In Bearings™

Structure

The new bearing is shown in Photo 1. It is very compact, including a one-way clutch within the boundary dimensions of standard deep groove ball bearing number 6205. The one-way clutch uses unique cams, which have a tough cross-sectional profile, to withstand heavy loads and shocks. The specially designed one-piece cage holds the cams and steel balls securely in place.

Features

■ Compact design
As Cam-in Bearings have the same dimensions (bore: ϕ25 mm × outside diameter: ϕ52 mm × width: 15 mm) as standard deep groove ball bearing number 6205, space is freed to allow greater flexibility in product design and more space for higher-capacity washing tanks.

■ Excellent torque characteristics
Resulting from the tough specially designed cams, the transmitting torque is high. The maximum transmitting torque is nearly eight times the rated torque.

■ Low noise
The one-piece cage, which holds the cams securely in place, and the garter spring ensure quiet running.

■ High sealing performance
With shields fitted on both sides, excellent sealing is achieved.

Performance

■ Wedging life test
Test conditions:

Load torque	42.1 N·m (4.3 kgf·m)
Number of wedging cycles	1 million
Ambient temperature	Room temperature (25°C)

Test result: No abnormality after 1 million cycles

■ Maximum transmitting torque
Test conditions:

Ambient temperature	Room temperature (25°C)
Measuring method	Increase static torque and measure the maximum transmitting torque

Test result: Maximum transmitting torque = 343 N·m (35 kgf·m)

■ Noise
Through testing of actual washing machines, we confirmed that noise was minimal during the spin cycle (i.e., while rotating in the unlocked direction).

■ Torque while rotating in the unlocked direction
Test conditions:

Speed	1 000 rpm
Axial load	29.4 N (3 kgf)
Ambient temperature	Room temperature (25°C)

Test result: Less than 4.9 N·m (500 gf·m)

Applications

Cam-In Bearings are now being mass-produced for washing machines. They are also suitable for one-way-rotating electric motors and material-handling and conveying equipment.

New Products

Maintenance-Free Precision Machinery Products with NSK K1™ Lubrication Units

A key developmental objective for rolling products is maintaining effective lubrication while extending maintenance intervals. Towards this end, NSK developed "Molded Oil" and used it to create NSK K1™ lubrication units for the various linear motion rolling products used in today's machines. Containing approximately 70 wt% lubricating oil, NSK K1 supply oil to rolling surfaces over an extended period of time. Since arriving on the market in early 1996, they have been well received for prolonging maintenance intervals and reducing costs. Now NSK has created the Maintenance-Free Series, a standardized line of products equipped with NSK K1. We are pleased to present it in this article.

The Maintenance-Free Series and Its Benefits

Figs. 1 through 5 illustrate the construction of the NSK Linear Guides, Ball Screws, Monocarriers, Robot Modules and Megathrust Motors in the Maintenance-Free Series. The installation of NSK K1 in these products provides the following benefits:

■ Extended maintenance-free intervals
When grease is used in combination with NSK K1, lubricating efficiency is retained over a longer period of time than existing products. For machines and equipment that are not easily supplied with lubricant, this is especially advantageous.

■ No contamination of surrounding environment
As products in the Maintenance-Free Series can be effectively lubricated with only a small amount of grease, they not only contribute to a cleaner environment but are also well suited to applications where contamination from oil must be prevented due to high cleanliness requirements.

■ Prolonged service life when products are exposed to water
In operating environments in which the products are exposed to water, either from the equipment they operate in being washed or from exposure to wind and rain, NSK K1, in combination with grease, prolong the service life.

■ Better performance in contaminating environments
Even in environments where the entry of foreign particles is unavoidable, the combination of NSK K1 and grease provides effective lubrication for a longer period of time and minimizes damage.

Conclusion

The market for linear motion products has long been demanding products that reduce maintenance time and costs. The Maintenance-Free Series, with its array of proven products, responds well to this demand.
We are confident that it will contribute substantially to reducing maintenance and costs, as well as improving the environment.

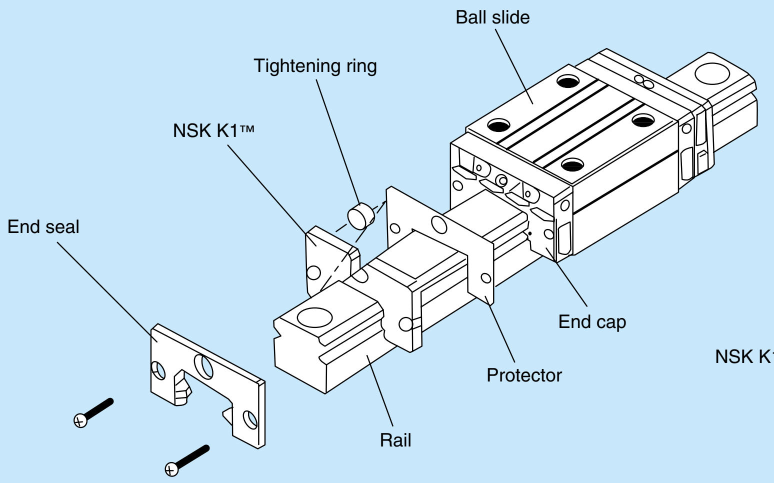

Fig. 1 Maintenance-Free Series NSK Linear Guide

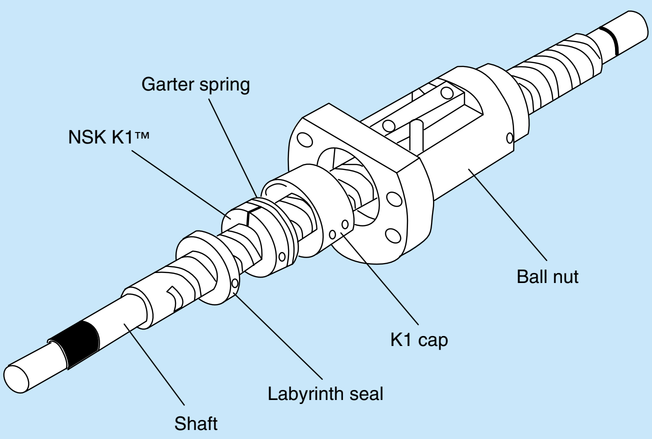

Fig. 2 Maintenance-Free Series Ball Screw

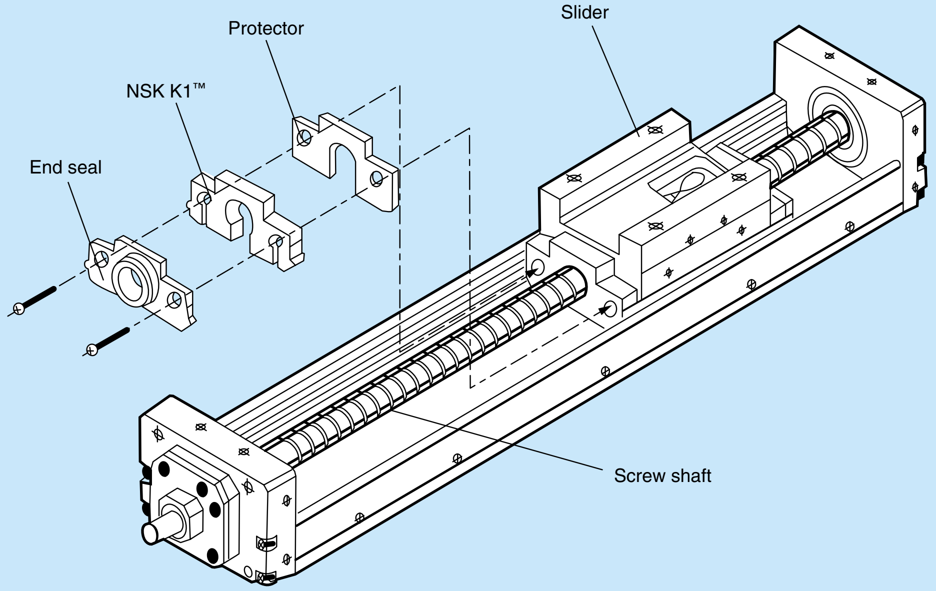

Fig. 3 Maintenance-Free Series Monocarrier

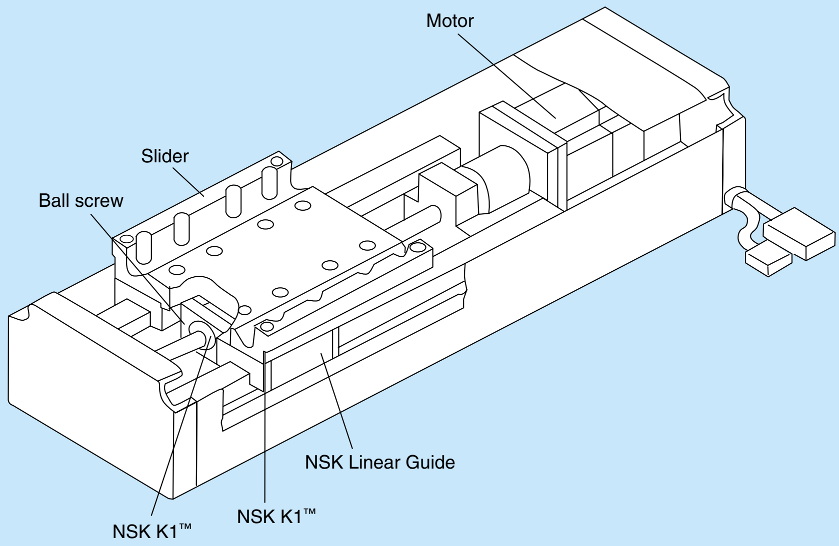

Fig. 4   Maintenance-Free Series Robot Module

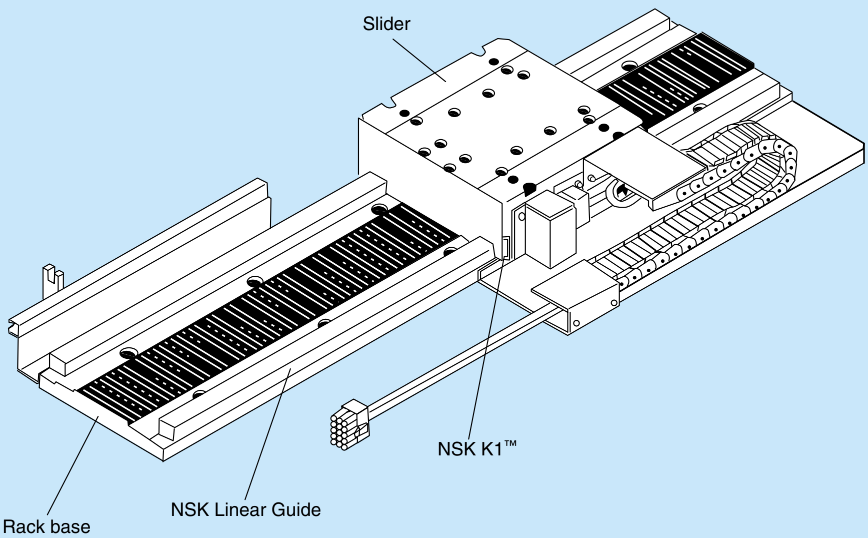

Fig. 5 Maintenance-Free Series Megathrust Motor

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