Performance of Hybrid Ceramic Ball Bearing for Turbochargers

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Recently, fuel-saving has been required for global environmental protection and energy saving in the automobile. Turbochargers are used as one of the means for improving the power of automobiles with small displacement engines. Acceleration responsibility and rotational performance (low torque, less vibration and low heat generation) at high rotational speeds, etc. are required on rolling bearings for turbochargers. "A floating bush bearing," which is a kind of slide bearing, is widely used for supporting the turbine shaft, and ball bearings are sometimes applied to improve rotational performance, for instance the acceleration responsibility. We developed hybrid ceramic ball bearings using silicon nitride ceramic balls for turbochargers, which have long life, low power loss, high seizure resistance and high durability, and started mass-production from 1998. This is the first adoption of hybrid ceramic ball bearings for passenger car turbochargers in the world.

This paper describes the performance of Koyo hybrid ceramic ball bearings for automotive engine turbocharger applications.

***Key Words**: ceramic ball bearing, silicon nitride, turbochrger*

1. Introduction

Recently, the fuel-saving of automobiles has been required for global environmental protection and energy saving. Turbochargers are used as one means of improving the power of automobiles with small engines. Bearings of turbochargers are required to have good acceleration response, rotational performance (low torque, low vibration, low temperature rise) at high speeds, etc. Journal bearings using a floating bush which are a kind of slide bearing, and hydrodynamic or hydrostatic thrust bearings are mainly used as support bearings of turbine shafts, and steel ball bearings are used for some engines to improve rotational performance of acceleration response, etc[1~5]. The ceramic material Koyo developed for ceramic bearings is HIP (hot isostatic pressing) sintered silicon nitride, which has been used commercially for over fifteen years. It has characteristics such as low density, heat resistance, high hardness, corrosion resistance, wear resistance, and so on.

Because of these superior characteristics, ceramic bearings are used in various applications, such as machine tools, semiconductor manufacturing equipment, and in applications with high temperatures and corrosive environments[6~10]. Furthermore, many evaluations have been performed in order to apply these bearings to aircraft and automobiles[11~14].

Making use of the excellent performance of silicon nitride, Koyo has developed hybrid ceramic ball bearings for turbochargers and started mass-producing them. This is the first adoption of hybrid ceramic ball bearings for passenger car turbochargers[15, 16] in the world.

2. Characteristics and Rolling Fatigue Life of Hybrid Ceramic Ball Bearings

Silicon nitride (Si_3N_4) is a high quality ceramic material with sintering aids yttrium oxide (Y_2O_3) and aluminum oxide (Al_2O_3) and subjected to hot isostatic pressing (HIP). **Table 1** shows the characteristics of silicon nitride compared with high temperature bearing steel AISI-M50. The main advantages when silicone nitride is used for turbocharger bearings are as follows.

1) Low density is effective for reducing bearings weight and centrifugal force of balls at high speed.
2) Covalent bond reduces seizure at oil starvation conditions at high speed.
3) Heat resistance makes high temperature applications possible.

Table 1 Characteristics of silicon nitride compared with AISI-M50

Item		Ceramic (Silicon nitride)	High temperature bearing steel (AISI-M50)
Heat resistance	K	1073	673
Density	g/cm^3	3.2	7.9
Thermal expansion coefficient	1/K	3.2×10^{-6}	10.6×10^{-6}
Vickers hardness	HV	1 400~1 700	700~800
Young's modulus	GPa	320	210
Poison's ratio		0.29	0.3
Corrosion resistance		Good	Not good
Magnetism		Non-magnetism	Magnetism
Electric conductivity		Insulator	Conductor
Bond of material		Covalent bond	Metallic bond

Higher reliability is required for automobile bearings. As reported before[17], rolling fatigue life of silicon nitride is superior to that of conventional bearing steel or high carbon chromium bearing steel (JIS-SUJ2 or SAE52100), and the failure mode is flaking similar to that of bearing steel, without instantaneous fracturing like a crash. In rolling fatigue life test of the bearings whose size was equivalent to that of JIS#696, the life of hybrid ceramic ball bearings was longer than the predicted life and flaking occurred only at steel inner raceways, and ceramic balls showed no failure[18]. Hybrid ceramic ball bearings are expected to have superior performance for turbochargers from the characteristics of silicon nitride and the results of rolling fatigue life test.

3. Performance Evaluation

3. 1 Evaluated Items and Methods

Table 2 shows main performance requirements and evaluated items. Since rolling fatigue life was mentioned in the previous chapter, this chapter deals mainly with mechanical loss and reliability.

Table 2 Required performance for turbochargers and evaluated items

Required performance		Evaluated item
Long life		Rolling fatigue life of ceramics
		Rolling fatigue life of hybrid ceramic ball bearings
Low mechanical loss		Constant speed performance
		Responsibility
Reliability	In clean oil	Anti-seizure properties
		Repeated axial load on-off durability
		Repeated on-off rotation durability
	In used oil	Repeated axial load on-off durability
	In contaminated oil	Repeated axial load on-off durability

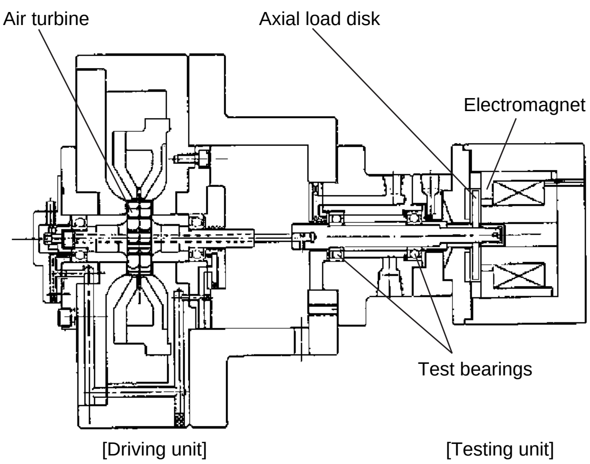


Fig. 1 Test equipment

Fig. 1 shows the test equipment. The test equipment is divided into the driving and testing sections. Test bearings in the testing section were rotated by air turbine in driving section. Test bearings can be rotated up to 140 000min^{-1} by changing air pressure supplied to air turbine. Lubrication can be selected as oil jet or oil mist.

3. 2 Performance of Mechanical Loss Reduction

3. 2. 1 Bearing Loss at Constant Speed

Fig. 2 and **Table 3** show the dimensions of the test bearing and its configuration. The test bearing was equivalent to an 708 angular contact ball bearing whose inner and outer rings were made of high-temperature bearing steel (AISI-M50) and balls of silicon nitride. The ball diameter was 5/32 inch (3.9688mm), and the bearing had seven balls and a cage made of polyimide resin whose heat resistance is excellent. **Table 4** shows test conditions under oil jet lubrication. These tests were conducted at the same feed oil pressure to compare bearing losses of hybrid ceramic bearings with those of floating bush bearings of equivalent shaft diameter.

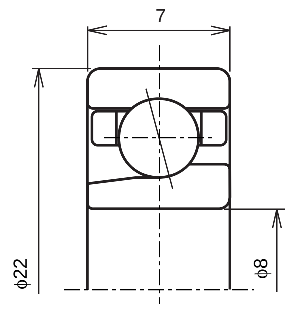


Fig. 2 708 test bearings dimensions

Table 3 Configuration of 708 test bearing

Item		Hybrid ceramic ball bearing
Inner and outer rings		AISI-M50
Ball	Material	Si_3N_4
	Diameter	5/32" (3.9688mm)
	Number	7
Cage		Polyimide resin

Table 4 Test conditions

Item		Condition
Rotational speed		120 000min^{-1} max.
Axial pre-load		0.12kN
Ambient temperature		Room temperature
Lubrication	Oil type	Aero-shell turbine 500
	Method	Oil jet
	Pressure	0.3MPa max.
	Amount	3.0 ℓ /min max.
	Temperature	313K

Fig. 3 compares the rotational speed between a hybrid ceramic ball bearing and a floating bush bearing changing the air pressure supplied to the air turbine. The rotational speed of the hybrid ceramic ball bearing was more than 10% higher than that of the floating bush bearing. **Fig. 3** also shows the rotational speed of just the air turbine from the drive section. Differences in rotational speed between the air turbine and the test bearings correspond to the frictional power losses of the test bearings (called the bearing frictional loss in this paper). Neglecting air and other friction losses of the air turbine, the rotational speed squared is proportional to rotational energy. This is shown in **Fig. 3**. When the rotational speed of just the air turbine without connecting to the bearing test section is N_0 and the rotational speed connecting to the bearing section is N_1, $N_0^2 - N_1^2$ is in proportion to the bearing frictional loss. The bearing frictional loss P_B is given by the equation (1).

$$P_B \propto N_0^2 - N_1^2 \qquad (1)$$

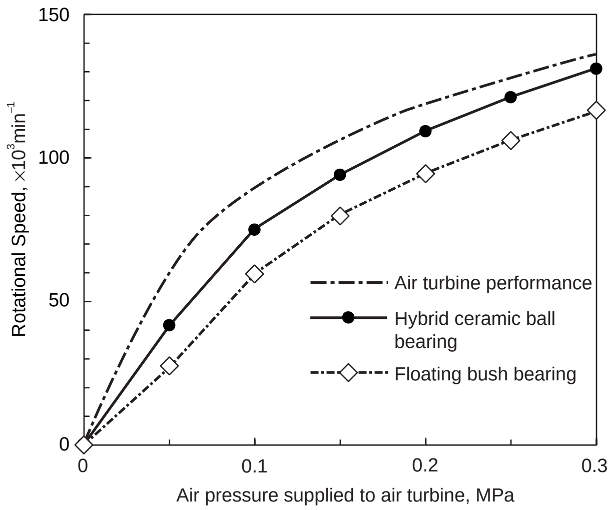


Fig. 3 Relationship between rotational speed and compressed air pressure

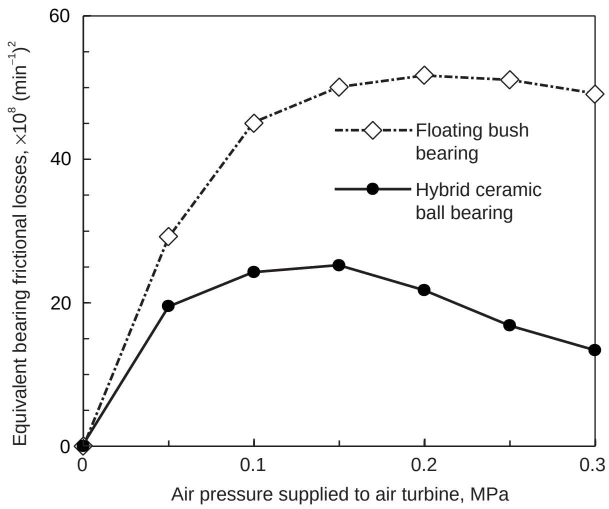


Fig. 4 Equivalent bearing frictional loss v.s. compressed air pressure

Fig. 4 shows the "equivalent bearing frictional loss," which corresponds to the difference between the speed of the air turbine squared and the speed of the test bearings in order to relatively compare with test bearings. Equivalent bearing frictional losses of hybrid ceramic ball bearings were 70% smaller than that of floating bush bearings.

3. 2. 2 Influence of Cage Materials

Test bearing dimensions and the test configuration are the same as those mentioned in **3. 2. 1**. The two cage materials were compared in **Table 5**. Density of polyimide resin is less than 20% of the density of high-tension brass. Test conditions are shown in the above-mentioned **Table 4**.

Table 5 Characteristics of cage materials

Item		Polyimide resin	High tension brass
Density	g/cm³	1.4	8.2
Elastic coefficient	GPa	3	110
Thermal expansion coefficient	1/K	41×10^{-6}	20×10^{-6}

Fig. 5 represents the test results under the same lubrication conditions. **Fig. 5** shows the relationship as ratios between equivalent bearing frictional losses and the compressed air pressure for hybrid ceramic ball bearings with polyimide resin or high-tension brass cages. The friction loss for hybrid ceramic ball bearings with polyimide resin cages was approximately 15% less than that for bearings with the high-tension brass cages at all rotational speeds. It was thought that because polyimide resin cages were 1/5 the density of the high-tension brass cages, the normal pressing load due to cage rotational run-out on the cage guiding surface of the outer ring shoulder by centrifugal force was reduced to 1/5.

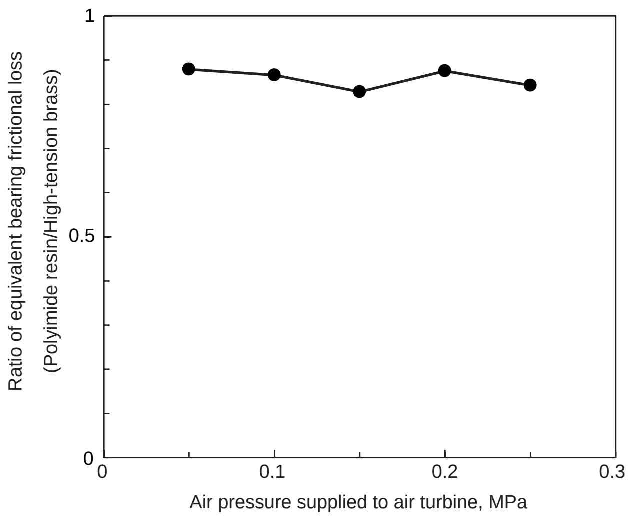


Fig. 5 Equivalent bearing frictional loss v.s. compressed air pressure (Influence of cage materials)

3. 2. 3 Influence of Cage Guidance

Fig. 6 shows the dimensions of the test bearings and **Table 6** shows their configuration. The test bearings were hybrid ceramic 798 angular contact ball bearings with inner and outer rings made of a specially developed bearing steel, KUJ7, used for medium-high temperatures[19]. The bearing had seven balls made of silicon nitride. The ball diameter was 1/8 inch (3.175mm). The cage was made of heat resistant polybenzimidazole resin. It was compared with both-side-outer-ring-shoulder-guidance (**Fig. 6 (a)**) and one-side-outer-ring-shoulder-guidance (**Fig. 6 (b)**) of cage outer diameter surface. **Table 7** shows test conditions.

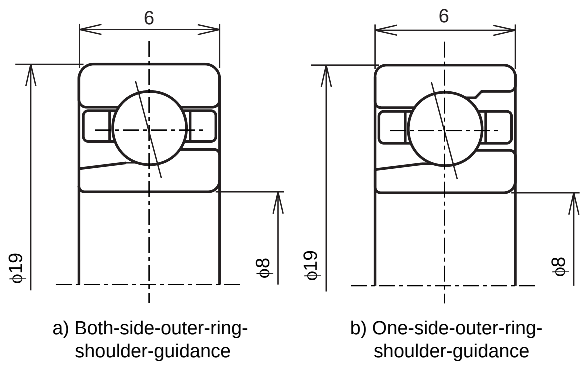


Fig.6 798 test bearing dimensions

Table 6 Configuration of 798 test bearings

Item		Hybrid ceramic ball bearing
Inner and outer rings		KUJ7[19]
Ball	Material	Si_3N_4
	Diameter	1/8" (3.175mm)
	Number	7
Cage		Polybenzimidazole resin

Table 7 Test conditions

Item		Condition
Rotational speed		120 000min^{-1} max.
Axial pre-load		0.1kN
Ambient temperature		Room temperature
Lubrication	Oil type	Engine oil 10W-30
	Method	Oil jet
	Pressure	0.3MPa max.
	Amount	3.0 ℓ /min max.
	Temperature	333K

Fig. 7 shows the comparison test results under the same lubrication conditions. **Fig. 7** shows the ratios between equivalent bearing frictional losses for hybrid ceramic ball bearings with one-side-outer-ring-shoulder-guidance and both-side-outer-ring-shoulder-guidance of cage outer diameter surface. The equivalent bearing frictional loss of hybrid ceramic ball bearings with one-side-outer-ring-shoulder-guidance was reduced by over 20% compared to that of both-side-outer-ring-shoulder-guidance. It is thought that the loss was reduced because the contact area of cage guidance of one side type became half that of both side type guidance.

From the results of both the last section and this section, it was found that when adequate cage material and cage guidance are selected, the frictional losses are respectively reduced to × 0.85 and × 0.8. Therefore, the overall frictional loss is able to be reduced by over 30%.

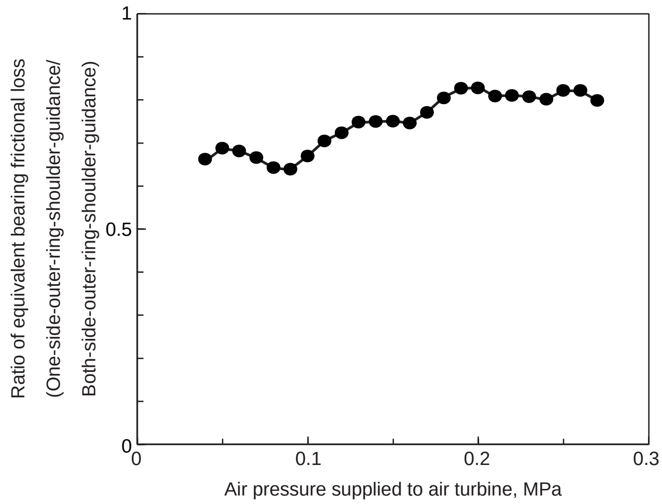


Fig. 7 Equivalent bearing frictional loss v.s. compressed air pressure (Influence of cage guidance)

3. 2. 4 Influence of Feed Oil Amount

Fig. 8 shows the dimensions of the test bearing, and **Table 8** shows its configuration. The test bearing was based on 7001 angular contact ball bearing. One type of hybrid ceramic ball bearing had inner and outer rings made of AISI-M50, a high-temperature bearing steel, and silicon nitride balls. The other test bearing's inner rings, outer rings, and balls were made of AISI-M50, high-temperature bearing steel. The ball diameter was 3/16 inch (4.7625mm). These bearings had ten balls and cages made of heat resistant polyimide resin. **Table 9** shows the test conditions. Results of these bearings were compared with those of floating bush bearings under the same feed oil pressure jet lubrication.

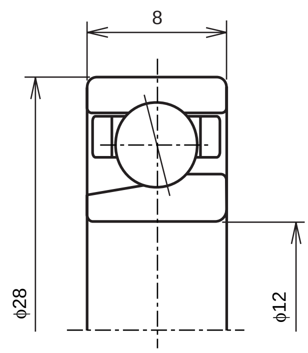


Fig. 8 7001 test bearing dimensions

Table 8 Configurations of 7001 test bearings

Item		Hybrid ceramic ball bearing	Steel ball bearing
Inner and outer rings		AISI-M50	AISI-M50
Ball	Material	Si_3N_4	AISI-M50
	Diameter	3/16" (4.7625mm)	3/16" (4.7625mm)
	Number	10	10
Cage		Polyimide resin	Polyimide resin

Table 9 Test Conditions

Item		Condition
Rotational speed		120 000min^{-1}max.
Axial pre-load		0.12kN
Ambient temperature		Room temperature
Lubrication	Oil type	Aero-shell turbine 500
	Method	Oil jet
	Pressure	0.3MPa max.
	Amount	0.023 ~ 3.0 ℓ /min.
	Temperature	313K

Fig. 9 shows a comparison of rotational speeds at a constant air pressure among three types of bearings (hybrid ceramic ball bearings, steel ball bearings and floating bush bearings) in several oil feed rates. The test was run at 0.1MPa and 0.3MPa air pressures, which represent low and high running speeds respectively. The rotational speeds of all types of bearings were increased because oil agitation resistance loss decreased when the oil flow amount was reduced. The rotational speeds of both rolling element bearings, were nearly same. The rotational speed of the floating bush bearings (a kind of sliding bearings) was significantly lower than that of the rolling element bearings. The difference of rotational speed was larger at low rotational speeds than at high rotational speeds. At high rotational speeds, the floating bush bearing and steel ball bearing seized when the oil flow was reduced. The hybrid ceramic ball bearings, however, did not seize even when the oil flow was reduced to 5% of the seizure limit oil amount for the floating bush bearing and 10% of the seizure limit oil amount for the steel ball bearings, so the tests were suspended.

Fig. 10 shows the equivalent bearing frictional losses in order to relatively compare the three types of test bearings. The compressed air pressure was 0.3MPa. The adequate oil flow amounts for the steel bearing and floating bush bearing are assumed to be five times the flow rates when these bearings seized. Since the hybrid ceramic bearing did not seize, its required oil flow amount is assumed to be five times the minimum tested oil flow rate. Comparison under the adequate oil flow rates for each type of bearings shows that the hybrid ceramic bearing has only 20% of the frictional loss of the floating bush bearing and 50% of that of the steel ball bearing.

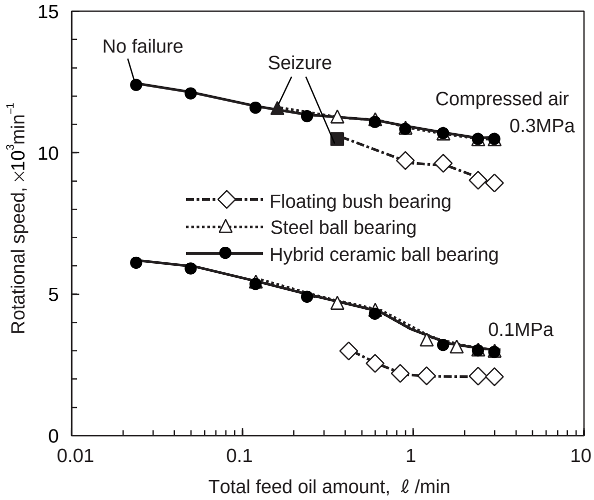


Fig. 9 Relationship between rotational speed and total feed oil amount

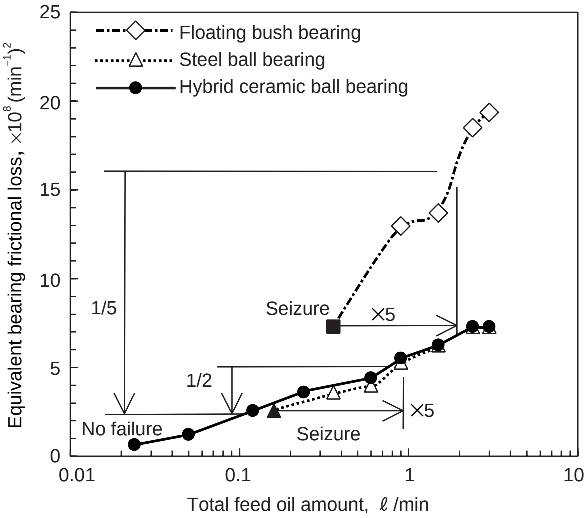


Fig. 10 Equivalent bearing frictional loss v.s. total feed oil amount

3. 2. 5 Bearing Fictional Loss at Various Rotational Speeds

In the previous sections bearing frictional losses have been discussed comparing rotational speed at constant rotational conditions. In this section, the acceleration response of the bearing rotational speed from a full stop and the deceleration response when the air supply from the air turbine is cut off are shown.

Test bearing dimensions, their configuration, and the test conditions are shown in **3. 2. 1**. The test bearings were hybrid ceramic 708 angular contact ball bearings. The acceleration response was studied by monitoring the speed versus time when 0.25MPa of compressed air was abruptly supplied to the air turbine in the drive section of the test equipment. Hybrid ceramic ball bearings were compared with floating bush bearings. Deceleration response was studied by monitoring the speed versus time when the compressed air supply was immediately stopped from an initial condition of 0.25MPa air pressure. Both types of bearings were lubricated by a constant 0.3MPa pressure oil feed.

Fig. 11 shows the acceleration response. The maximum air turbine speed was 120 000min^{-1}. The hybrid ceramic ball bearing took 10% less time to reach 60 000min^{-1} (50% of 120 000min^{-1}) than the floating bush bearing. The hybrid ceramic ball bearing took 20% less time to reach 90 000min^{-1} (75% of 120 000min^{-1}) than the floating bush bearing. Consequently, hybrid ceramic ball bearings have better acceleration response than floating bush bearings.

Fig. 12 shows the deceleration response. The required time to stop the hybrid ceramic ball bearings was 60% better than that in the case of floating bush bearings. Consequently, the rotating resistance of hybrid ceramic ball bearings is significantly less than that in the case of floating bush bearings.

The acceleration test data from **Fig. 11** was used to calculate power. The acceleration at each speed was used to calculate each power for the air turbine, floating bush bearing and hybrid ceramic ball bearing. **Fig. 13** shows the bearing frictional losses of hybrid ceramic ball bearings and floating bush bearings, as calculated from the power based on **Fig. 11**'s data and the constant of this test system. Bearing frictional losses for the hybrid ceramic ball bearings were about 0.2kW less than that of floating bush bearings in the 80 000 to 100 000min^{-1} speed range.

Fig. 14 shows the power loss as the bearing decelerates. This was calculated using the test data from **Fig. 12**, as in the case of **Fig. 13**, calculated using the test data from **Fig. 11**. **Fig. 14** shows bearing frictional losses of hybrid ceramic ball bearings and floating bush bearings, which was calculated from power losses derived from **Fig. 12**'s data. The bearing frictional losses for the hybrid ceramic ball bearings during deceleration were about 0.2kW less than that of floating bush bearings in the 100 000 to 60 000min^{-1} speed range. Power loss during deceleration was, on average, about 40% less than that during acceleration in the case of the hybrid ceramic bearing and about 20% less in the case of the floating bush bearing.

As mentioned above, it was experimentally confirmed that the mechanical losses could be reduced when hybrid ceramic ball bearings were used at both constant and changing rotational speed.

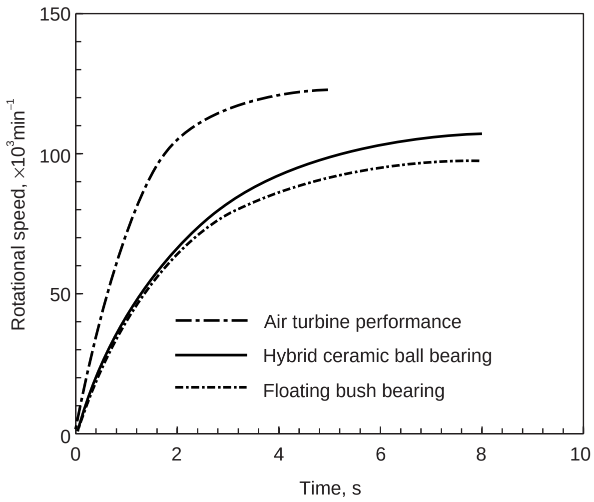


Fig. 11 Acceleration response

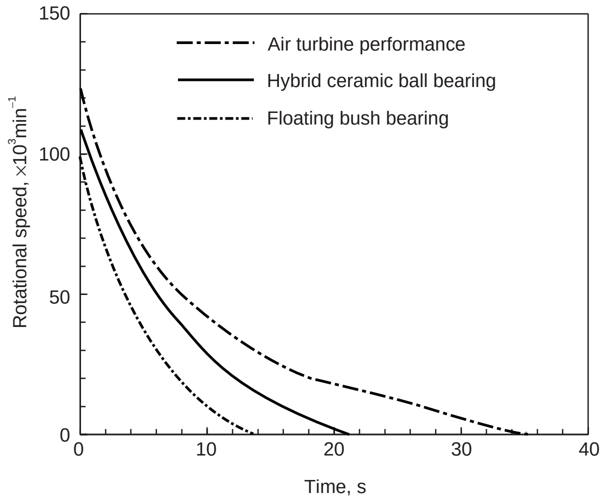


Fig. 12 Deceleration response

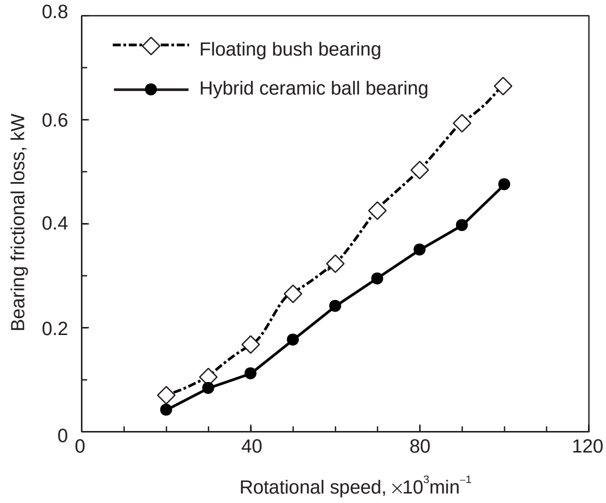


Fig. 13 Bearing frictional losses during acceleration v.s. rotational speed

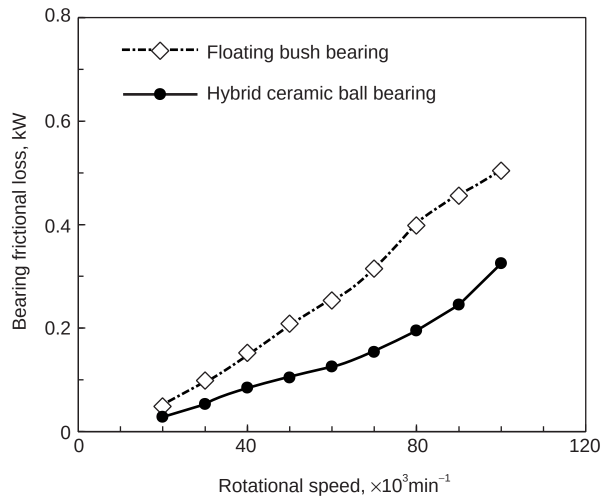


Fig. 14 Bearing frictional losses during deceleration v.s. rotational speed

3. 3 Durability and Reliability of Bearings

3. 3. 1 Performance of Anti-Seizure

The test data including the contents concerning performance of anti-seizure is already indicated in the section **3. 2. 4**. In this section it describes anti-seizure performance in detail for more understanding.

From **Fig. 9**, at high rotational speeds of compressed air pressure 0.3MPa, under maximum feed oil amount 3 ℓ /min the rotational speed of floating bush bearings was stable and about 17 000min^{-1} lower than that of hybrid ceramic ball bearings. However, when oil feed amount reduced, the increase rate of the rotational speed was the fastest, so the rotational speed difference was reduced. When oil feed amount was below 0.4 ℓ /min, temperature of the floating bush bearings rose and the bearings seized. As the contact area of slide bearings is remarkably lager than that of rolling bearings, much amount of lubricating oil is considered to be required in order to make stable oil film. Steel ball bearings stably rotated at nearly the same rotational speed as hybrid ceramic ball bearings under maximum feed oil amount 3 ℓ /min. When oil feed amount reduced, the rotational speed of the steel ball bearings became slightly higher than that of the hybrid ceramic ball bearings, because of its higher temperature rise, and the bearings seized below 0.2 ℓ /min oil feed amount. The hybrid ceramic ball bearings, however, did not seize even when the oil flow was reduced to 5% of the seizure limit oil amount for the floating bush bearing and 10% of the seizure limit oil amount for the steel ball bearings, so the tests were suspended. Hybrid ceramic ball bearings showed better anti-seizure performance than other bearings under little lubricating oil amount. It is considered that because hybrid ceramic ball bearings have covalent-bonded ceramic balls, they have no metal to metal contact under high oil starvation at high rotational speed and are protected against early adhesion, wear and so on.

3. 3. 2 Repeated Axial Load ON-OFF Durability

From this section, test conditions where loading and unloading or rotation and stopping is cyclicly repeated are shown as "ON-OFF" conditions.

The durability of hybrid ceramic ball bearings and steel ball bearings were tested in filtered new clean oil, 20 000km used oil, and oil contaminated by high-speed-steel powder.

First, repeated axial load ON-OFF durability on hybrid ceramic ball bearings was conducted in filtered new clean oil.

The test equipment, the dimensions of the test bearings and their configuration are the same in **Fig. 1**, **Fig. 6 (a)** and **Table 6** respectively. The test bearings were hybrid ceramic 798 angular contact ball bearings. Oil jet lubrication with filtered clean oil was used.

Fig. 15 shows the condition of axial load ON/OFF cycle. Rotational speed at no load condition (but only axial pre-load) was controlled and fixed to 120 000min^{-1} by compressed air pressure and it provided ON/OFF axial loading of 100 000 cycles (1 cycle = 3s, ON = 0.6kN × 1.5s, OFF = 0kN × 1.5s). The purpose of this durability test is a durability evaluation under various conditions of ball spin sliding because it gives varied contact angles of balls and rolling element load to inner and outer ring raceways by changing axial load. In this test condition the variable range of contact angle is 8.4 degrees given by numerical study considered centrifugal force, and rolling element load under loading condition becomes 6 times higher compared to in the no load condition.

Fig. 16 shows the repeated axial load ON-OFF durability test results. The durability tests were conducted two times. Using filtered clean oil, the hybrid ceramic ball bearings showed stable low vibration with no damage after 100 000 ON/OFF (ON : 0.6kN, OFF : 0kN) loading cycles at 120 000min^{-1}.

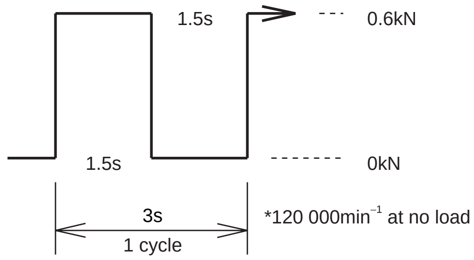


Fig. 15 Cycle of axial loading

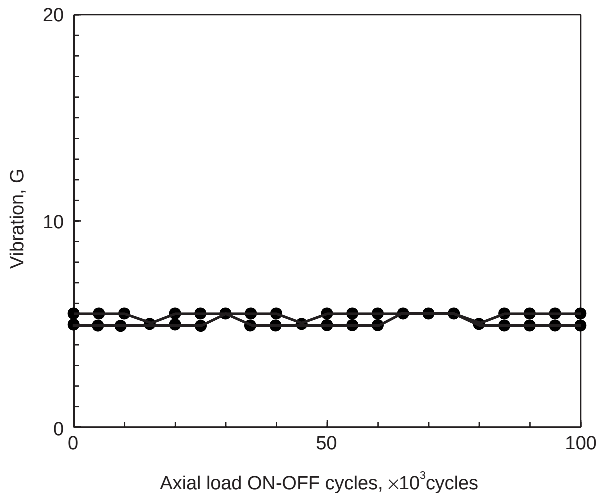


Fig. 16 Repeated load ON-OFF durability test results

3. 3. 3 Repeated Axial Load ON-OFF Durability in Used Oil

Second, the durability of hybrid ceramic ball bearings was compared to steel ball bearings in the used oil of 20 000km.

The test equipment, the bearing dimensions and the test conditions are the same as **Fig. 1**, **Fig. 6 (a)** and **Table 10**. Their configuration is showed in **Table 11** in order to compare with hybrid ceramic ball bearings and steel ball bearings. Hybrid ceramic ball bearings are the same as **Table 6**. The hybrid ceramic ball bearings were compared to steel ball bearings with inner and outer rings made of KUJ7, Koyo semi-high temperature bearing steel, and balls made of SKH4, JIS high-speed steel. In this test, two conditions were different from the previous condition. First, the lubricant was engine oil that had been used for 20 000km service. The other, the rotational speed was reduced to 100 000min^{-1} due to increased vibration.

Table 10 Test conditions

Item		Condition
Rotational speed		120 000min^{-1}
Axial pre-load		0.1kN
Axial load		ON : 0.6kN, OFF : 0kN (Cycle : See in **Fig 15**)
Ambient temperature		Room temperature
Lubrication	Oil type	Engine oil 10W-30
	Method	Oil jet
	Pressure	0.3MPa max.
	Amount	3.0 ℓ /min max.
	Temperature	343K

Table 11 Configuration of 798 test bearings

Item		Hybrid ceramic ball bearing	Steel ball bearing
Inner and outer rings		KUJ7[19]	KUJ7
Ball	Material	Si_3N_4	SKH4
	Diameter	1/8" (3.175mm)	1/8" (3.175mm)
	Number	7	7
Cage		Polybenzimidazole resin	Polybenzimidazole resin

Fig. 17 shows the durability test results in the used oil. Two kinds of bearings were respectively tested two times. The vibrations of the steel bearings increased earlier than in the hybrid ceramic ball bearings. The steel ball bearings tests were suspended at 32 000 to 40 000 cycles due to high vibration levels. The hybrid ceramic ball bearing's vibration increase was less than 50% to the original level even at 100 000 cycles. The durability tests could have been continued. From the appearance of the ceramic and steel balls, since only steel balls showed rough surface, they apparently contribute to the early vibration increase of steel ball bearings.

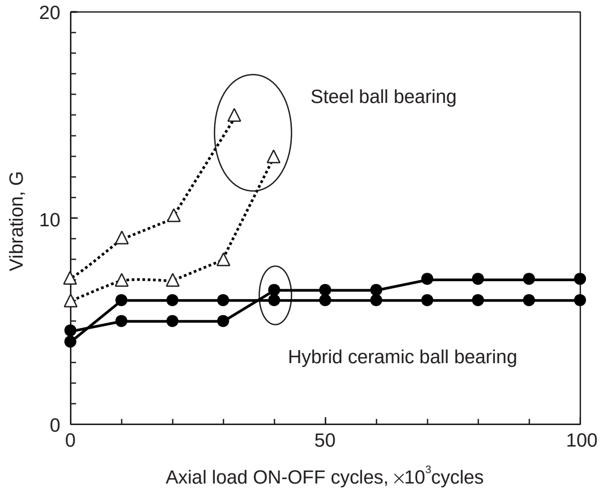


Fig. 17 Durability test results in 20 000km used oil

3. 3. 4 Repeated Axial Load ON-OFF Durability in Contaminated Oil

The bearing dimensions, their configuration and the test conditions are shown in **Fig. 6 (a)**, **Table 10** and **Table 11**. In this section the hybrid ceramic ball bearings were compared to the steel ball bearings, too. Two test conditions, however, were different. First, the lubricant was the oil contaminated with 60ppm of 27μm average sized high-speed steel powder with and Vickers hardness of 800 to 900 HV. Second, the rotational speed was 100 000min^{-1}, the same for the used oil durability tests, due to increased vibration.

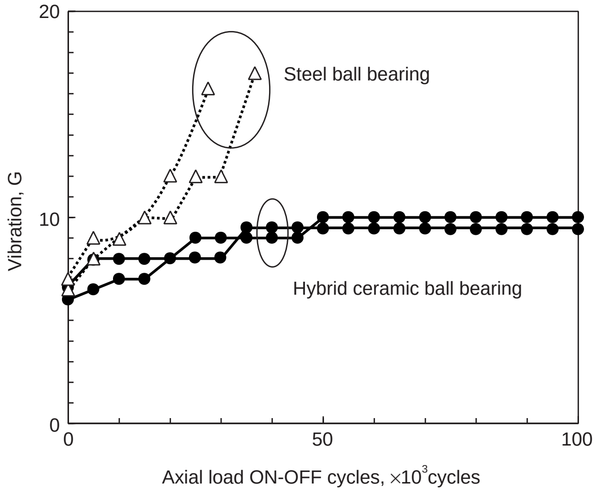


Fig. 18 Durability test results in contaminated oil with 0.027mm high-speed steel powder

Fig. 18 shows the durability test results in the contaminated oil. Two kinds of bearings were respectively tested two times. The steel bearings vibration level increased earlier than the hybrid ceramic ball bearings. At 28 000 to 38 000 cycles, the durability tests were suspended due to high vibration. The vibration level increased even earlier than for the used oil test. For the hybrid ceramic ball bearings, the vibration increase was less than 50% even at 100 000 cycles. The durability tests could have been continued. The vibration values, however, were about 50% higher than those from the used oil test.

Fig. 19 compares the wear amount of components between the hybrid ceramic ball bearings and the steel ball bearings after testing . In this figure the amounts of wear were obtained from the radius measurement. For the steel ball bearings, which were suspended at 28 000 to 38 000 cycles, the ball and inner ring raceway wear were about 5μm. The outer ring raceway wear were 2μm to 3μm. On the other hand, the hybrid ceramic ball bearings, even at 100 000 cycles, had no damage to the ceramic balls. The wear of the inner and outer rings were only 1μm to 2μm. **Fig. 20** compares the appearance of the ceramic and steel balls. It is considered that the balls, the inner and outer ring raceways were worn by the roughened surface of the steel balls same as seen in the durability test in used oil. Since the ceramic balls in hybrid ceramic bearings had enough high hardness against the contamination they were not damaged. It is considered that they apparently did not contribute to the damage of the inner and outer ring raceways. Furthermore, ceramic balls of hybrid ceramic ball bearings were not damaged by silicon carbide powers with Vickers hardness of 2 500 HV harder than the high speed steel powders[20]. They showed superior performance in contamination.

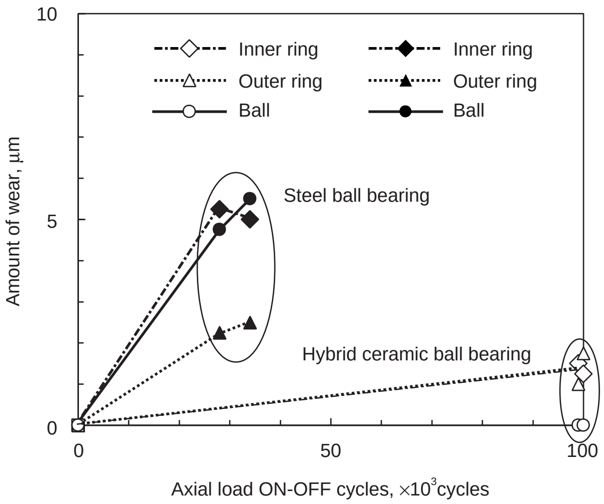
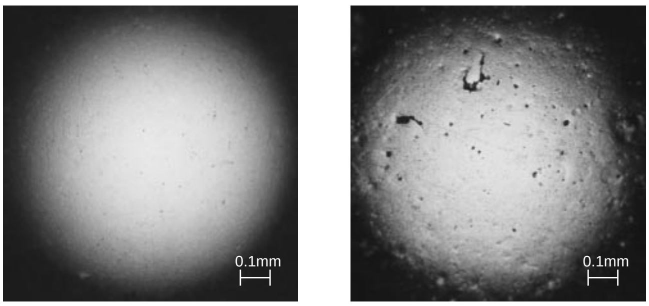


Fig. 19 Component wear in contaminated oil with 0.027mm high-speed steel powder



(a) Ceramic ball (b) Steel ball

Fig. 20 Photograph of ceramic and steel balls after durability test in contaminated oil with 0.027mm high-speed steel powder

3. 3. 5 Repeated ON-OFF Rotation Durability

The bearing dimensions and their configuration are the same as in **Fig. 8** and **Table 8**. In order to see the performance difference between hybrid ceramic ball bearings and steel ball bearings, full complement ball bearings, without a cage, were tested. The test bearings were equivalent to 7001 angular contact ball bearings. The first bearing was a hybrid ceramic ball bearing with AISI-M50, high-temperature bearing steel, inner and outer rings and silicon nitride balls. The other test bearing was a steel ball bearing with AISI-M50, high temperature bearing steel, inner and outer rings and balls. The ball diameter was 3/16 inch (4.7625mm). Since the bearings were full complement, they had thirteen balls. **Table 12** lists the test conditions. Oil mist lubrication was used to highlight the difference in performance.

Table 12 Test conditions

Item		Condition
Rotational speed		ON : 120 000min^{-1}
		OFF : 0min^{-1}
		(Cycle : See in **Fig 21**)
Axial pre-load		0.12kN
Ambient temperature		Room temperature
Lubrication	Oil type	Velocity No. 6
	Method	Oil mist
	Pressure	0.1MPa
	Amount	0.09 ℓ /h
	Temperature	Room temperature

Fig. 21 indicates the condition of rotation ON/OFF cycle. Rotational speed at ON condition was controlled and fixed to 120 000min^{-1} by compressed air pressure and ON/OFF cycles repeated by open/close of electromagnetic valve. At ON condition the rotation was provided by immediately controlled compressed air supply to air turbine, which is the drive section of the test equipment, opening electromagnetic valve from stop condition. After that for thirty seconds it was held until the rotational speed reached to 120 000min^{-1} and kept stably. At OFF condition the rotation of the test bearings was stopped by immediate shut of controlled compressed air supply to air turbine from 120 000min^{-1} rotational speed condition. OFF time determined in sixty seconds on account of rotational complete stop. Therefore, one cycle of ON-OFF is in ninety seconds. A purpose of this durability test is the durability estimation under wider range changes of ball spin sliding than that of the repeated axial load ON-OFF durability test because it is varied motion of balls and rolling element contact to inner and outer ring raceways by immediate change of rotational speed.

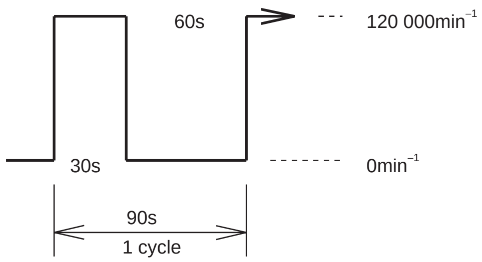


Fig. 21 Cycle of rotaional speed

Fig. 22 shows the repeated ON-OFF rotational speed durability test results. Two kinds of bearings were respectively tested two times. Steel ball bearings seized after 2 or 3 cycles, but the hybrid ceramic ball bearings were not damaged at 1 000 cycles, and could continuously being tested. It is considered that the clear difference between two types of bearings was caused by oil starvation after taking place the phenomenon of contact between two adjacent balls especially at acceleration because of there being no cage. Sliding happens in contact area between two balls as their rotational directions are opposite. It is assumed that steel balls adhere to themselves and suddenly seize when oil starvation occurs in the contact area. It is considered that ceramic balls did not seize when they contacted themselves because of no metal contact.

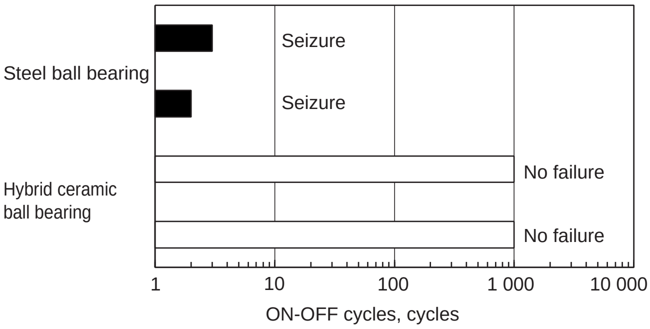


Fig. 22 Repeated Go-Stop rotational speed durability test

4. Conclusions

The performance of silicon nitride hybrid ceramic ball bearings for use in turbochargers was evaluated. The following results were obtained.

1) At constant rotational speed, bearing frictional losses of hybrid ceramic ball bearings were over 30% less than those of floating bush bearings.
2) The bearing frictional losses of hybrid ceramic ball bearings could be decreased to about 50% that of floating bush bearings and to about 20% that of steel ball bearings when the required oil flow rate reduced to minimum suitable amount without seizure.
3) Bearing frictional losses of hybrid ceramic ball bearings using cages made of polyimide resin were over 15% less than those using cages made of high-tension brass.
4) Bearing frictional losses of one-side-outer-ring-shoulder-guidance was over 20% less than that of both-side-outer-ring-shoulder-guidance.
5) In acceleration and deceleration tests, the frictional losses of hybrid ceramic ball bearings were up to 0.2kW less than those of floating bush bearings.
6) Frictional losses during deceleration were about 40% and 20% less than those of the acceleration test for the hybrid ceramic ball bearing and floating bush bearing respectively.
7) Hybrid ceramic ball bearings did not seize even under about 10% of the oil feed amount of where the steel ball bearings seized and under 5% of the oil feed amount where the floating bush bearings seized, and anti-seizure performance was superior to them.
8) For repeated axial load ON-OFF durability tests, the hybrid ceramic ball bearings were not damaged.
9) Hybrid ceramic ball bearings had more than three times higher durability than steel ball bearings when tested in the 20 000km used oil and the oil contaminated by high-speed steel powder.
10) High-speed steel contaminants had a stronger influence to the test bearings than the used oil, and gave higher vibration.
11) For steel ball bearings, high-speed steel contaminants caused wear on all the balls, inner and outer rings. The hybrid ceramic ball bearings, however, had no wear on the balls and little wear of inner and outer rings.
12) For repeated ON-OFF rotational speed durability tests, the steel ball bearings seized early, but the hybrid ceramic ball bearings did not seize and were not damaged.

As mentioned above, hybrid ceramic ball bearings for turbochargers offer the practical solution for long life, low friction losses, superior seizure resistance and long durability.

Appendix

Power losses for the accelerate and decelerate change in rotational speed were calculated as follows.

The moment of inertia of a rotating system is I , neglecting changes to I with respect to time and air friction and other losses. Angular velocity is ω (rad/s). Torque relative to rotational speed is τ_A (N·m). τ_A is given by the equation (1).

$$\tau_A = I\frac{d\omega}{dt} \tag{1}$$

Power loss, P_A (W), used to the increase rotational speed is given by the equation (2).

$$\begin{aligned} P_A &= \frac{d}{dt}\int I\frac{d\omega}{dt}d\theta \\ &= I\frac{d}{dt}\int \omega \cdot d\omega \\ &= I\omega\frac{d\omega}{dt} \end{aligned} \tag{2}$$

Replacing angular velocity ω with rotational speed n, the constant peculiar to this system (including I) is α, so the equation (1) can be replaced to the equation (3).

$$P_A = \alpha n\frac{dn}{dt} \tag{3}$$

By reading the change in rotational speed n, with respect to time for hybrid ceramic ball bearings, floating bush bearings, and the air turbine which represents air turbine performance, power losses P_A used to increase rotational speed can be calculated.

In the same way, power losses resulting in decreased rotational speed can be calculated. The torque for decreasing rotational speed is τ_D (N·m). τ_D is given by equation (1').

$$\tau_D = I\frac{d\omega}{dt} \tag{1'}$$

Therefore power losses P_D (W) used to decrease rotational speed is given by the equation (3').

$$P_D = \alpha n\frac{dn}{dt} \tag{3'}$$

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