Study of motorized spindle reliability monitoring

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Abstract: This paper proposes an intelligent monitoring system to adapt motorized high speed spindle on machine tools to meet the requirement of Industries 4.0, based on the techniques of power electronic engineering, mechatronics and reliability engineering. When a real-time spindle bearing life monitoring unit is applied, energy control and smart machining technology functions are performed with superior results. Raw data is transmitted though a filter to create fruitful information and allow the remote monitoring system to operate effectively. . The information supports predictive maintenance plans and improves the quality of after-sales service.

Keywords: Intelligent Monitoring; Industries 4.0; Reliability Engineering

I. **Introduction**

A key factor in the most competitive manufacturing industries is the ability to manage complex industrial processes continuously. Different tasks are frequently performed by numerous venders in various geographical locations, which had been successfully achieved for several decades by employing information and communication technology (ICT). More than 90% of all industrial manufacturing processes are supported by ICT.

At present, powerful autonomous microcomputers are increasingly wirelessly networked with one another and covered by internet communication. This is resulting in the convergence of the physical and virtual world in the form of cyber-physical-systems (CPS). It is therefore possible to network resources, information, objects, and people to create the internet of things (IoT) and services, and this phenomenon will also have an effect on industry. In the manufacturing realm, this technological evolution can be described as the fourth-stage revolution. To achieve their goals, manufacturers expect high operational reliability and data link availability, which are crucial for mechanical and automation engineering. Guaranteed latency times and stable connections are thus key issues, since there have a direct impact on application performance. Furthermore it is beneficial to integrate the different established perspectives that currently exist in the realms of production, mechanical, process, and automation engineering, IT and the Internet, as well as knowledge and procedures of total quality management. [1].

Leading manufacturers allow individual, customer-specific criteria to be included in the design, configuration, ordering, planning, manufacture, operation phases, and enable last-minute changes to be incorporated, such manufacturer need not be huge production plants. Flexible, CPS-based ad hoc networking enables dynamic configuration of different aspects of business processes. Furthermore, engineering processes can be made more agile, manufacturing processes can be changed, temporary shortages can be compensated for, and huge output increases can be achieved within a short time.

With optimistic decision-making, an update facility provides end-to-end transparency in real time, allowing early design decisions verification for engineering techniques. These are more flexible responses to disruption and global optimization across all sites of a company in the production area. Resource productivity and efficiency, the overarching strategic goals for industrial manufacturing processes, applying the highest possible production output from a given source volumes, and using the lowest possible amount of resources are important, to deliver a particular output for management. CPS enables manufacturing processes to be optimized on a case-by-case basis, across the entire value network, which is the aim of the industry 4.0. [2].

In term of supplying such a highly reliable production solution, the equipment produced needs to be of stable and reliable quality, and it should be possible to predict the mean time between failures (MTBF). Monitoring the complete set of equipment and its components becomes possible, and the production working conditions can be shared from management. A pre-check equipment warning message can provide enough time to the service team to ensure appropriate service and production remain on track.

The aim of the new equipment and concept is to improve the computerization, digitalization, and intelligence of manufacturing techniques. The goals of fourth industrial revolution differ significantly from those of the third. Not only are new industrial techniques created, but the aims is also to integrate the current relative industrial technology, sales, and products, to build smart factories that are adaptive, information-efficient, and ergonomic. Thus, vendor collaboration, business partners, and the value chain offer complete information for high productivity and competition. The technical theory is the intelligent collaborative monitoring system and IoT, which can create a perceptive new intelligent industrial manufacturing chain.

By mean of big data analysis, a new product offering resolutions can be created to completely satisfy customers. Computer predictions, such as temperature, metropolitan transportation, and market research, can be applied as data-base evaluations to enable real-time management control or support dispatch resources, as well as reduce additive costs and waste (amelioration of value chain). Fig.1 illustrates the concept of company’s management plan and the manner in which total quality management operates.

As an equipment provider and machine tool supplier, it is extremely important to emphasize the use of the technical applications of IoT and data mining. This is to produce an intelligent machine for offering a product with predicable MTBF, a complete after-sales service plan, and real-time production, as well as provide analysis to support manufacturing management in creating the production program, input control, and output delivery timing. Furthermore, a full-time manufacturing management plan should be arranged.

In other words, when a product is operating in the field, regardless its location, the product manufacturer should be able to predict its life time and monitoring of machine working condition should be possible. In the case of a part deteriorating or before it stop working, it should be possible to set the time before failure occurs and the service team can arrange an appointment with the user. in this case, the service does not interfere with the original production plan. The user will be able to perform the production plan in optimization, ensuring that the user remain competitive and most profitable.

In *Reliability and MTBF Overview-*, speaks provides two categories for estimating the reliability of electronic equipment: (1) prediction based on individual failure rates, and (2) Demonstration based on operation of equipment over time. These prediction methods have several common assumptions, for example, constant failure rate, the use of thermal and stress acceleration factors, quality factors, and use conditions. [3]

Kumar, Knezevic and Croker J. proposed two mathematical models, developed to predict the maintenance free operating period survivability (MFOPS):, one using the mission reliability approach, and the other applying alternating renewal theory. This paper also analyses the cost implications of MFOPS for the customer and producer. [4]

Huh, Kim and Yi constructed a monitoring system on the basis of a new scaled Kalman filter with model error compensator (SKFMEC), which was developed to improve the robustness in the performance of Kalman filter methods. The SKFMEC technique employs both the well-conditioned observer and model error compensator concepts. [5].

Kim et al, proposed the peck drilling method, using thrust force signal monitoring. The authors introduced monitoring parameters for peck drilling through the analysis of thrust force in both the time and frequency domains. [6].

Torell and Avelar calculated MTBF based on an observed sample of similar systems, usually performed after a large population has been deployed in the field. MTBF estimation is by far the most widely used method, mainly because it is employed on real products that undergo actual application in the field. It is, therefore, critical that the manufacturer understands the most appropriate method for the given application. [7].

The high speed motorized spindle has been applied in various fields for decades, and monitoring of spindle thermal growth and vibration has been studied extensively. However, spindle life-time has not been studied much. High maintenance and long machine down time cost the user significantly, and spindle MTBF has become an important significant issue. Life-time monitoring provides valuable information to the user and equipment provider by offering a smart system to provide a service prior to its failure, save spindle down time, and minimize repair costs.

II Smart machine design

To achieve life-time monitoring, it is necessary to develop products based on application of industries segment , which means that market research on segment of application required, A precise Autocad ANSYS simulation is conducted, which serves to ensure that the products will meet the feature and capability requirement of the original input. It is extremely important to have a static analysis and dynamic Model in place before the product undergoes commercial production. This technique ensures effective condition for production operation, which is the goal of the reliability promise (RP), energy management (EM), and smart manufacturing process (SMP).

The smart manufacturing process function concepts are divided into four layers. The first layer is for key component measurement and data collection, where data is collected using sensors attached to the key components. The second layer obtains data via real-time monitoring of all motion components, where all data collected is uploaded to the cloud after initial processing, and real-time monitoring reports and management, the data in order to detect weaknesses. The third layer is for data analysis, in which, mathematical calculations are performed to process the data uploaded on the cloud and convert it into more valuable information, The fourth layer is the human machine interface (HMI), where the processed data is transformed for the control to obtain a precise analysis of the machine condition. The four-layer system is shown in Fig. 1.

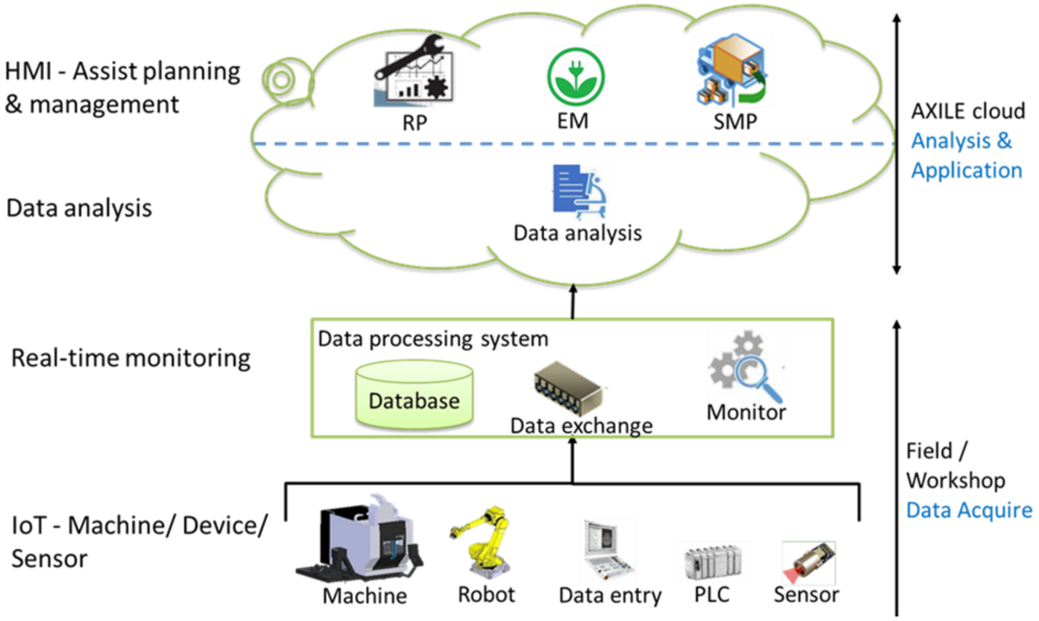


Fig. 1 Four Layers Design

III. Function features

Here provide a description of three functions to meet the smart machine requirement as follows.

1.Reliability promise

The RP manages the monitoring function of the wear-out and damage of key components, while the component lifetime is lower than the default value (set at 2-weeks). This function provides notification to facilitate the maintenance procedure and maintain the machine in highly reliable state to avoid unprepared machine rundown.

Fig. 2 illustrates the hazard rate bathtub curve. The hazard rate of components at the useful life stage increases gradually. Once the hazard rate surpasses the useful life and reaches the wear-out stage, the hazard rate increases significantly and components may be damaged at any time. Therefore, predictive maintenance is necessary prior to components reaching the wear out stage.

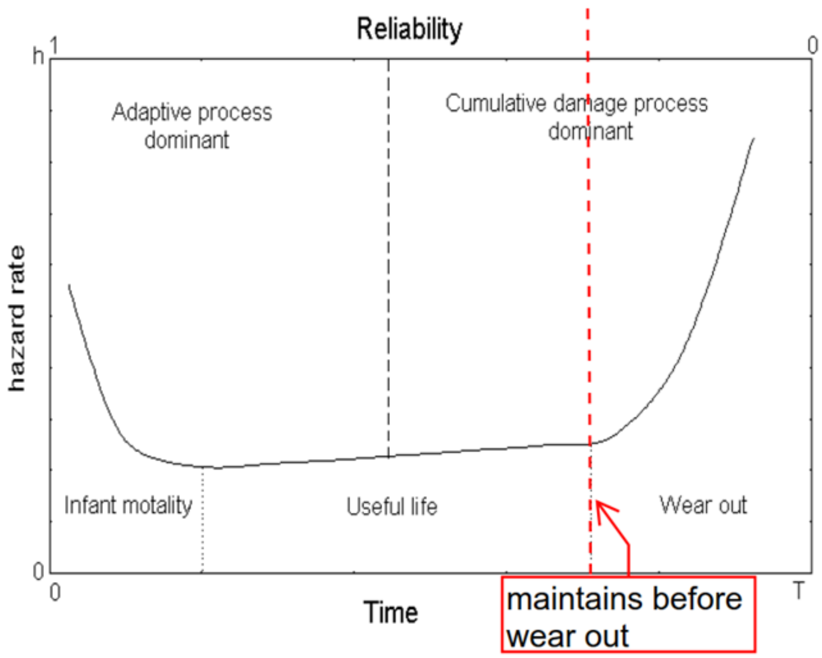


Fig. 2 Hazard rate bathtub curve

Key component lifetime is evaluated by mean of real-time and lifetime monitoring. Real-time monitoring ensures the function of monitoring key component conditions, whereas lifetime monitoring uses MTBF and then compares this with actual usage time. A warning message will appear once undesirable conditions have been reached.

2.Energy management

The EM system is a function based on the ISO14966 standard. Its six objectives are as follows:

1) Use energy efficiently

2) Reduce the machine function in saving costs (for customer),

3) Increase metalworking competitiveness,

4) Improve organization and brand image,

5) Remain innovative and creative,

6) Improve product knowledge,

An EM system helps engineers to compare production processes systematically, and optimizes machining parameters or uses energy consumption parameters to evaluate whether tools are damaged. Therefore, managers can make decisions based on energy consumption in each production line to obtain maximum profit.

3.Smart manufacturing process

Using the machining progress and condition feedback from machines allows users to understand production conditions and plan for further optimization of the production process.

The SMP enables users to understand machining progress more clearly.

It furthermore aids management in achieve the targets of smart factory production. Big data provides all the necessary information for decision-making. And this process results in competitive production.

2. Spindle failure

The motorized spindle has become the most popular tool when applying high-speed machining. its performance indicates significantly improved tolerance of fine machining, as well as fast cutting time, which cuts out a large percentage of energy usage, while high-speed cutting saves a lot of processing time. Furthermore, the machining parts are no longer required to move between different machines and set up fixtures from time to time, allowing for better performance. High-speed machining is one of the key factors in leading machining technology. [8].

High-speed machining provides significant benefits in cutting applications, particularly hard material machining. However, high-speed spindle is at high cost per unit, and damage may occur easily, due to lack of maintenance and unexpected collisions. Fig. 3 shows the major reasons for bearing failure. The summary indicates that 80 % of damage was result of external faults. It is therefore extremely important to ensure that the bearings always operate under normal condition, and a real-time monitoring system is essential. Moreover, the spindle design should be adapted to MTBF modes. The operator can always be certain about the spindle life, and the production cost is well considered in term of about wearing-out costs. The spindle is always active whenever the application is expected, in this way, a reliable spindle meets the requirement of a reliable device adapting to the requirements of the fourth industrial revolution (Industries 4.0).

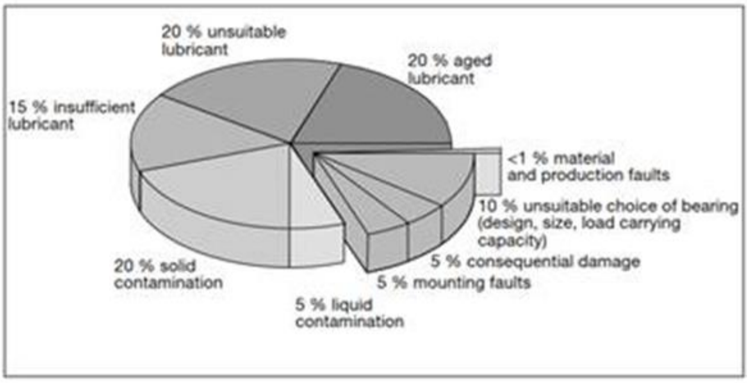


Fig 3 Bearing failure analysis (Info: FAG)

Failure modes for bearings have been discussed, as indicated in the above figure. The modes are classified as fatigue, wear, correction, plastic deformation, fracture, and electrical erosion. The main causes of failure include loss of lubrication, incorrect mounting of bearing, misalignment, over- load, and excessive load. Since the external load, for example, cutting force on tool, acts directly on the bearing, bearing failure is strongly associated with these stresses. Therefore, it is essential to consider the appropriate force acting on the spindle. In this paper, a systematic approach to the applicability of a given bearing configuration is discussed. The failure rate calculation, as well as the life-time of each bearing, and a bearing configuration, are defined. Both the natural intrinsic characteristics of the bearing configuration and the external force are examined.

2.1 Bearing failure rate

Bearing arrangement

It is difficult to acquire a bearing arrangements design that is perfectly adapted to the environmental unknown environment, and to predict its life. Therefore, similar speculations and prior experiences may help to shape the primary design of bearing arrangements. Factors to be considered in the design include bearing type, parameters, and lubricant methods. The bearing type is depend on basic applications, such as angular contact bearings and roller bearings, bearing preload methods include the commonly used position preload, spring preload, and constant pressure preload. Basic bearing parameters include the materials of angular contact ball bearings, roller body, and bearing cages, as well as the interference of aspects such as the rings and shaft. The spindle speed, bearing life, and loading applied on the rotating shaft system are dependent on the design of the basic parameters.

The following conditions should be considered in the design of bearing arrangements:

1) Bearing arrangements
2) Preload force device selection
3) Working temperature of bearings and environmental temperature
4) Cooling conditions
5) Loading condition

2.2 Life time, failure rate, intrinsic characteristics, and safe operating area of bearings

Once the bearing arrangement has been determined, the influence of the bearing load, acting on the bearing system and each bearing, can be analyzed, and a given system's performance can be evaluated. Next, the metrics of bearing dynamic loads such as contact pressure of the inner/outer ring, P, spin-roll ratio γ, and the operating contact angle α_2 can be calculated. Furthermore, the failure rate of each bearing and that of the overall bearing system are calculated. Finally, the safe operation area of this bearing design can be determined by mean of the limited parameters of bearing dynamic loads.

1) Life-time and failure rate of a single bearing

Several quantification methods are used to calculate the life of a single bearing. The most commonly used method, shown as equation (1), can simply be found in technical manuals of bearing manufacturers. The physical mechanism that causes failure is the degree of force, which is transformed into contact pressure between the surface of a rolling body and inner/outer ring of a bearing. The safety factor, the C/P parameter, is defined, where: the rated axial load C represents an endurance force on the bearing, which can be found in the manufacturer's bearing manual. According to metal fatigue theory, the higher the safety factor, the longer the bearing life will be. In general, the C/P parameter can be used to conduct a basic evaluation. However, this depends on the operational environment and lubrication factors.

In modern industrial applications, the working and environmental factors are considered to identify to affect the bearing life, thus, equation (1) is modified to become equation (2). In 2007, the International Organization for standardization released ISO 281:2007; equation (3) is adopted more frequently [5]. The subscript letter "n" in (2) and (3) represents the possibility of failure, for example, n=10, (L10), indicates that the reliability of bearings is 90%, while, n=1, (L1), means the reliability of bearings is 99%.

$$L_{10} = \alpha \left(\frac{C}{P} \right)^{b} \frac{B}{N} \tag{1}$$

where

L_{10} : Life-time as the failure possibility is equal to 10 %, in hours

α : Life adjustment factor

b : Based on bearing type. b=3, for ball bearings; b=10/3 for roller bearings

C : Radial-rated bearing load rating

P : Applied dynamic equivalent radial load on bearings

B : Factor depending on method and unit used in the equation

N : Rotating speed of the bearings

$$L_{n,a} = a_1 a_2 a_3 L_{10} \quad (2)$$

where

a_1 : The adjustment factor for requisite reliability depends on the failure probability, for instance, $a_1 = 1$ for_L_{10}, which is 90 % reliability. $a_1 = 0.64$ for_L_5, which means 95 % reliability and 5 % un-reliability.

a_2 : The factor for manufacturing methods, such as the forming method, material process2 and heat treatment.

a_3 : The factor for operating conditions, including lubrication, contamination and misalignment.

$$L_{n,a} = a_1 a_{iso} L_{10} \quad (3)$$

where

a_{iso} : The correction factor for the influence of lubrication, contamination, and fatigue limit load. a_{iso} is a function of the aforementioned parameters.

2) Failure rate calculation for bearing configuration

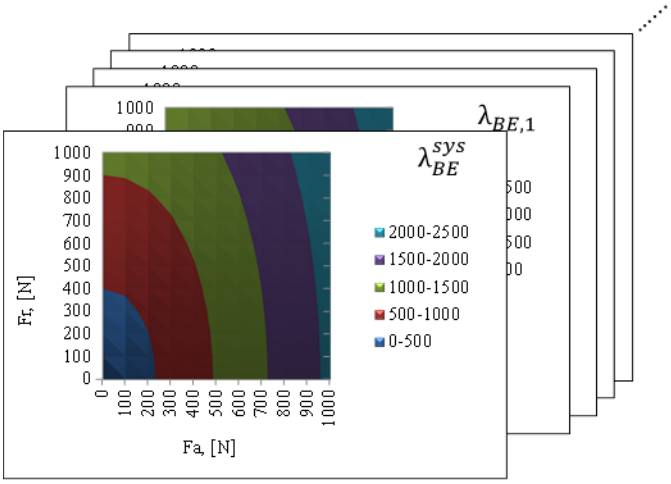
Suppose there is a bearing system, in which the configuration is composed of a number of bearings. In this bearing configuration, the bearing functionality is irreplaceable, therefore, it is regarded as a series-connected model and the total failure rate λ_{BE}^{sys} is calculated as follows:

$$\lambda_{BE}^{sys} = \sum_{i=1}^{n} \lambda_{BE,i}^{sys} = \sum_{i=1}^{n} \frac{1}{L_{a,i}}, \quad (4)$$

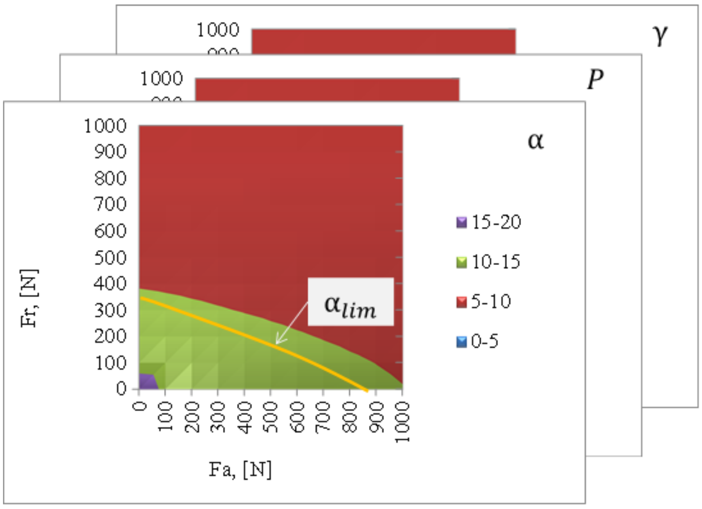
where

$$L_a^{sys} = \lambda_{BE}^{sys},$$

The cutting force should be divided into two components, the axial force Fa and radial force Fr. two independent variable factors and one dependent variable factor exist, and the distribution diagram of the intrinsic bearing properties includes three axes to present this information. An example of the intrinsic bearing characteristics is shown in Fig. 4. There are several distribution diagrams, including that of the failure rate, contact stress, and spin-roll ratio. The other diagrams can be illustrated as well, depending on whether the parameters are significant. The data in the distribution diagram are applicable only to the specific design and operating conditions. Once the bearing preloading design and/or operating speed of the spindle is changed, these data parameters are no longer applicable. According to the bearing safety parameters, each distribution diagram can be divided into several parts to identify the appropriate working areas, such as safe, sub-safe, risk, and high-risk work zones, as illustrated in Fig. 5.



(1) Distribution diagram of failure rate (λ_{BE}^{sys} and $\lambda_{BE,i}$)



(2) Distribution diagram of contact angle, contact press, and spin-roll ratio

Fig. 4 Diagram of intrinsic bearing characteristics chart- for a specific speed condition

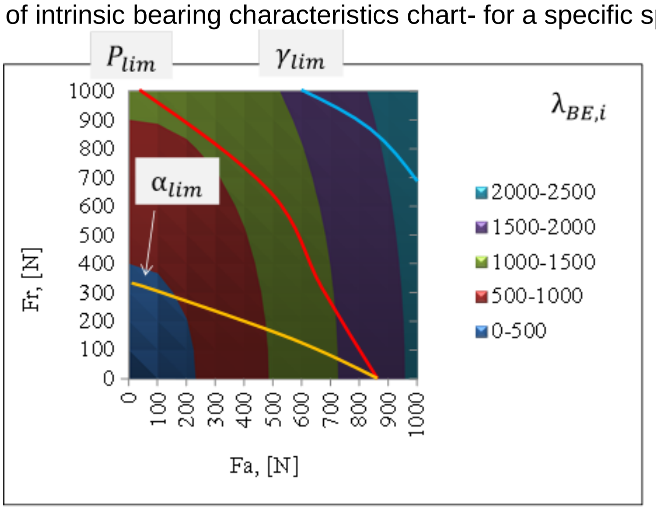


Fig. 5 Diagram of working area for a single bearing

2.3 Cutting failure rate calculation in a given cutting process

1) Given a simplified cutting process

To reduce processing time and achieve greater rigidity in metal-cutting processes, several cutting properties are essential, such as heavy cutting, high-speed milling, high-speed metal removal rate, and high precision. In the rotating system, these properties are represented with the requirements of cutting force and power, spindle speed, and work period.

Furthermore, the changing scope of cutting power and spindle speed may be relatively high, particularly in the application of high-speed motorized spindles. However, because of their complexity, these dynamic cutting properties are not appropriate for analysis. To simplify the analysis process, the complicated cutting conditions should be simplified into several important and representative metrics, such as basic spindle speed, power, and time.

(a) Cutting failure rate analysis of each bearing and the bearing system

In this step, the cutting failure rate for a given cutting process is obtained by mean of equation (5), in this paper, it is referred to as the cutting failure rate, λ_{BE}^{cut}. The processing is equivalently simplified for all cutting condition and he cutting life time L_a^{cut} is presented in equation (6).

$$\lambda_{BE}^{cut} = \sum_{j=1}^{N} U_j^{process} \lambda_{BE,j}^{process} , \quad (5)$$

Where

$\lambda_{BE,j}^{process}$:Fail rate of the j-th cutting process

$U_{BE,j}^{process}$:Duty cycle of the j-th cutting process

j :The j-th cutting process

$$L_a^{cut} = \frac{1}{\lambda_{BE}^{cut}} , \quad (6)$$

3. Case study

Bearing system and its arrangement

To explain the relation between aforementioned lifetime, failure rate and metrics of bearing dynamic loading, a case study is discussed. The bearing configuration of this case is illustrated in Fig 6. In this case study, there are four bearings, including the shaft, in the bearing system design, and the bearing arrangements are assembled using the face-to-face method. The first two bearings and the next two are of the same size and code, and the spring preload is selected. The axial force Fa and radial force Fr are applied to the front of the shaft, which represents the cutting force applied, and this force ranges from 0 to 3000 N. Owing to limited space, only the analyzed data of the bearing surface stress parameter is shown below. The maximum contact pressure of the bearing P_{max} is 2000N/mm^2.

（1） Analyzed results of the intrinsic characteristics of bearing configuration

The bearing failure rate and life-time for the case study are shown in Fig. 7 and 8, respectively. Due to the exponential relationship within the Probability Density Function distribution for bearing, the failure rate and life-time are reciprocal, as the failure rate increases, the bearing life-time decreases. Furthermore, the greater the cutting force applied to the system, the lower the expected bearing life. In addition, when the bearings are not influenced by an exterior force, that is, $F_a = F_r = 0$, the life-time of the four bearings are differ..

However, using only the analyzed result of failure rate and lifetime is insufficient for judging whether the bearing system can meet user requirements. Apart from the application requirements (failure rate and life-time), it is necessary to consider the metrics of bearing dynamic load and loading conditions. As aforementioned, the limitation of the loading condition for bearings should be deliberated, such as mentioned previously, the loading condition limitations for bearings, such as the contact pressure P and contact angle α, should be considered. The working boundary should be drawn in the distribution diagram, and the safe operation area od such a system should be examined.. Taking the case study as an example, as shown in Fig. 9(a) and 9(c), bearing no. 1 and 3 are high risk, because of the high contact pressure on the ring surface, which cause metal fatigue damage. As the boundary line, the external force acting on bearing

Nos_1,3, is mapped in Fig. 8(e), and a new distribution diagram is obtained for examination, as shown in Fig 8(f). It is clear that the safe operation boundary is surrounded by three lines, namely the vertical axis, horizontal axis, and curve of the boundary, for the two bearings. Although the safe operation area is provided by the aforementioned curves, it is preferable to operate this system under the maximum contact pressure P_{max}, indicated by the blue-dotted curve in Fig. 8(f).

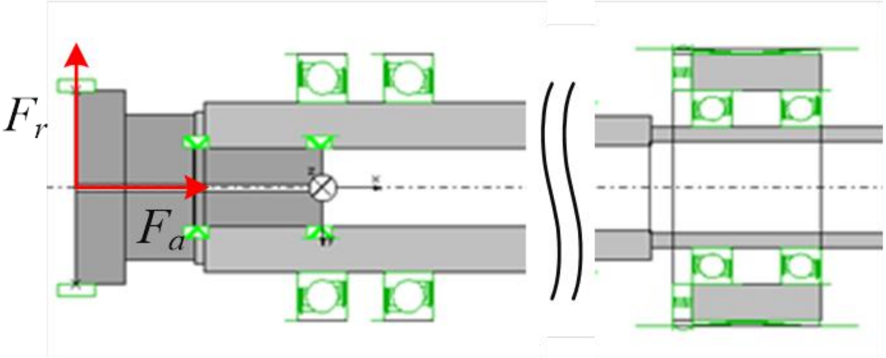


Fig. 6 Bearing arrangements of motorized spindle (not to scale)

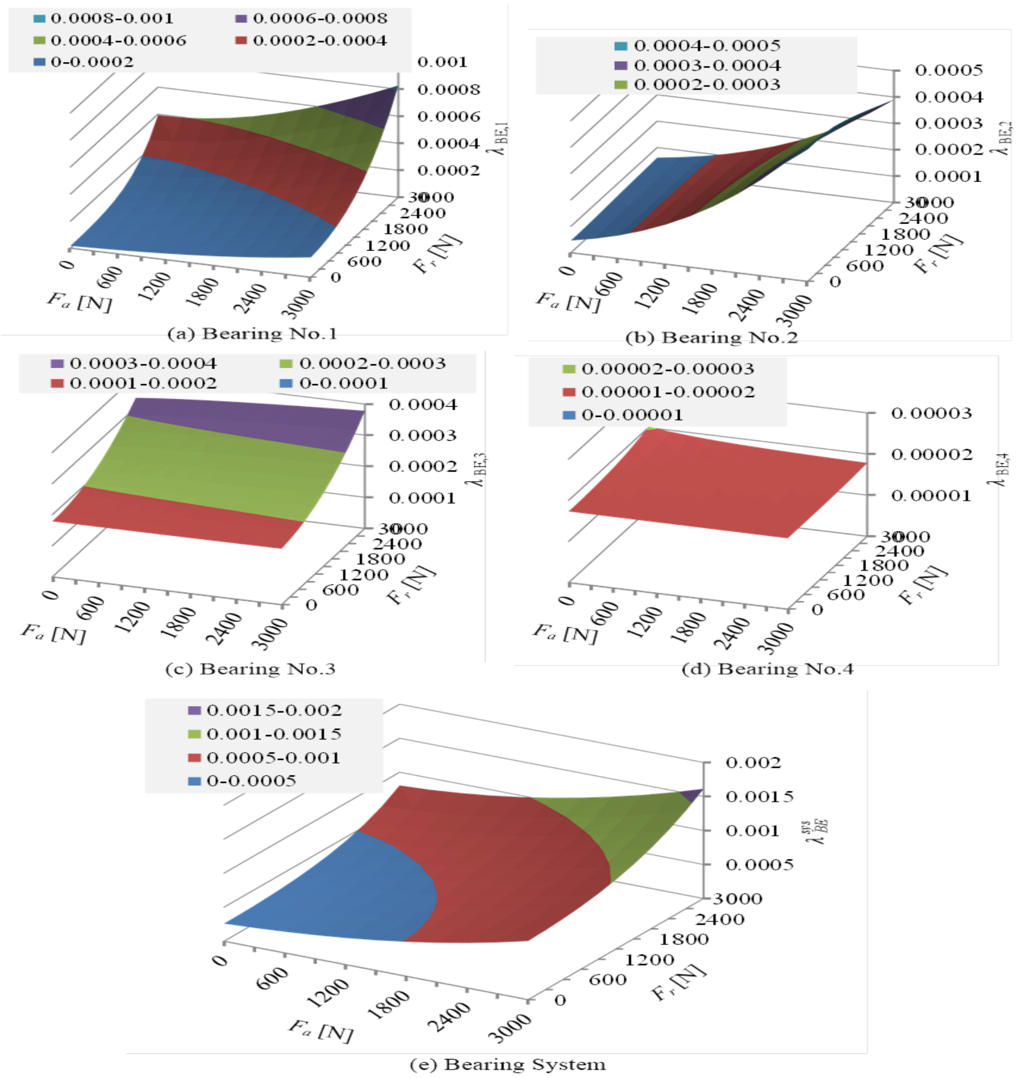


Fig. 7 Distribution diagram of failure rate for each bearing

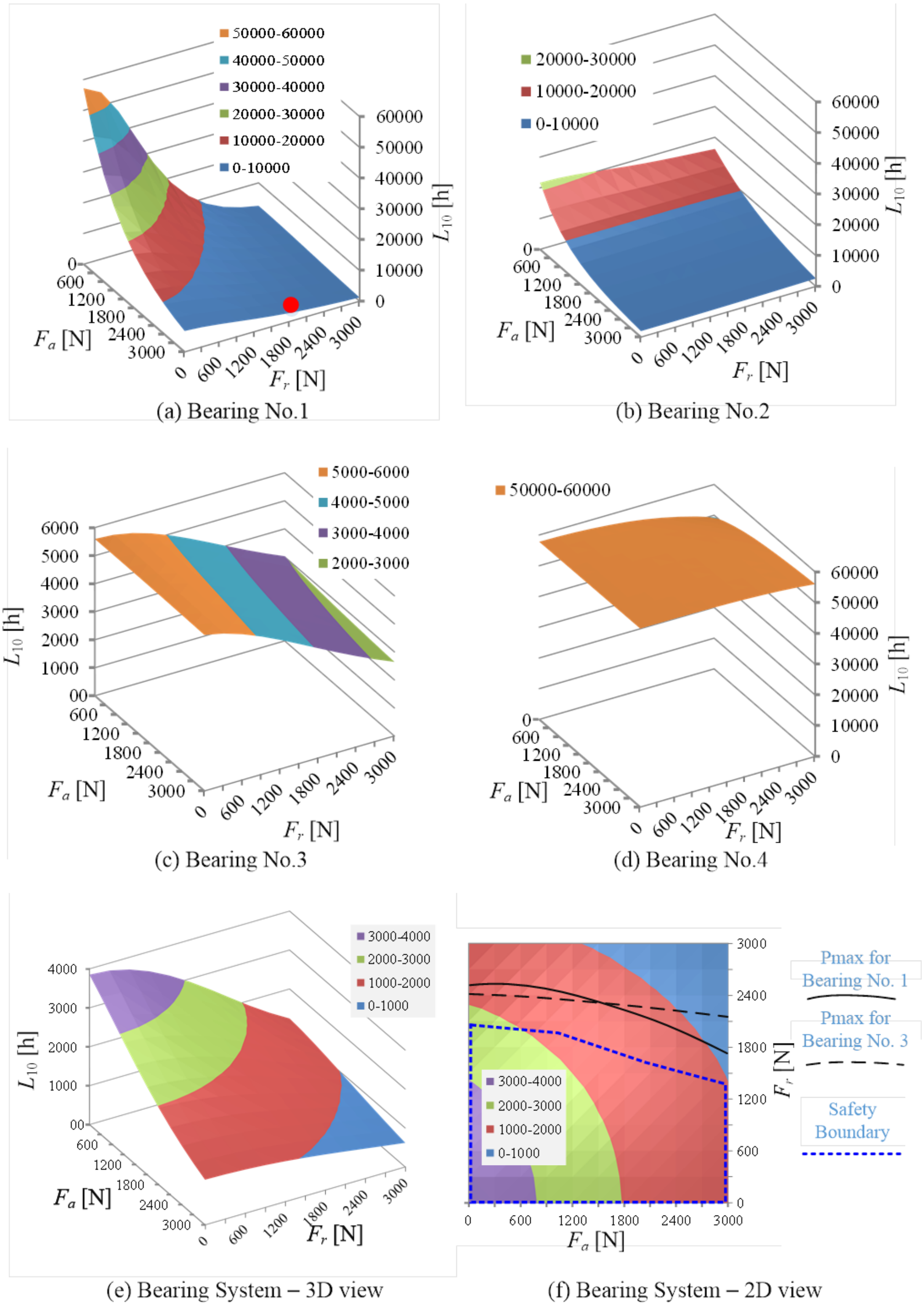


Fig. 8 Distribution diagram of life-time for each bearing

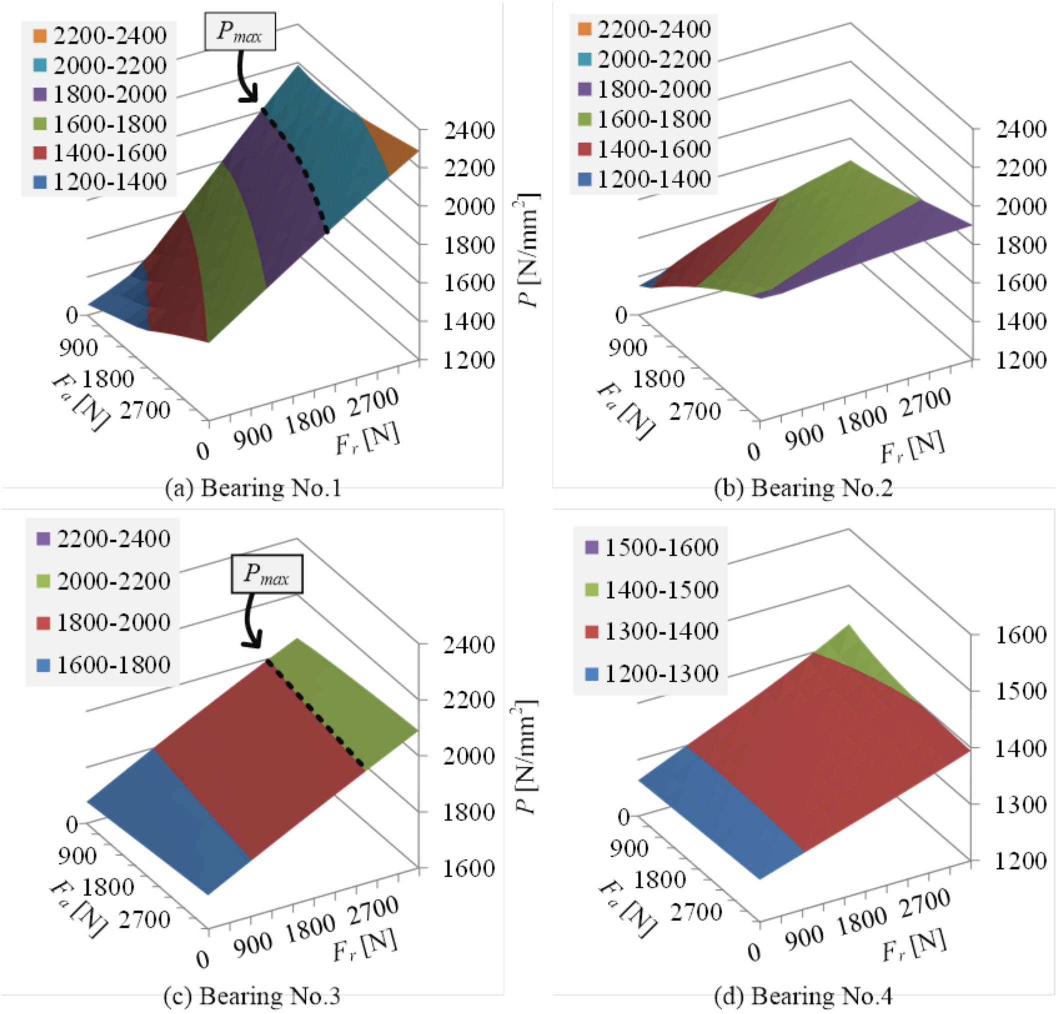


Fig. 9 Distribution diagram of bearing surface pressure

(2) Bearing failure rate for a given cutting process

The cutting process is considered, and the cutting processes parameters for bearings are displayed in Table 2. The case study included four cutting processes under the highest spindle speed. Process no.1 indicates that the spindle bearing system is placed without an external cutting force. Furthermore, the operation of the machine tool is assumed to be only in the axial direction, and the cutting tools are not in contact with the workpiece. Technically, process no. 1 requires less time, only 10%; process no. 2 is considered as fine finishing for a smoother surface. Therefore, the feed rate and force on bearing are lower, whereas the processing time is longer.

According to the loading force on the shaft in Table 1, and the intrinsic bearing characteristics, presented in section 3, the failure rate and lifetime for the given bearing configuration are determined and given in Table 2. As the bearing system operates during a specific cutting process, the cutting failure rate λ_{BE}^{cut} and life-time L_a^{cut} are 3.91e-4 and 2620_h, calculated by mean of equations (5) and (6), respectively. Because the cutting failure rate is obtained from the multiplication of $\lambda_{BEi}^{process}$, $U_i^{process}$ and $U_i^{process}$ are between 0 and 1. Therefore, the cutting failure rate will be between that of the highest and lowest of the original failure rate, and the cutting life-time exhibits the same characteristic.

Table 1 Parameters for a given cutting process

Cutting Process	F_a [N]	F_r [N]	[%] Percentage for the processing time
No. 1	0	0	10
No. 2	300	300	60
No. 3	300	1200	10
No. 4	2400	1200	20

Table 2 Failure rate and life time of bearing system for a given cutting process

Cutting Process	Life time for a cutting process L_{10}^{sys} [h]	Failure rate for cutting process $\lambda_{BE,j}^{process}$	Duty cycle $U_i^{process}$
No. 1	3851	2.60e-4	0.1
No. 2	3498	2.86e-4	0.6
No. 3	2970	3.37e-4	0.1
No. 4	1334	7.49e-4	0.2

To calculate the bearing lifetime and effectively evaluate the reliability of the main spindle system, selection of the sub-bearing is an important factor, it is necessary to determine the exterior force which influences the bearing lifetime. Considering that the force imposed and that of the bearing system can be used to analyze the system life and bearing dynamic load in order to obtain the bearing intrinsic characteristics, this paper indicates not only the main spindle life important, but that the bearing dynamic load conditions (such as surface pressure and contact angle.) should be considered in order to understand the failure mechanism and avoid the current system design that does not meet the force requirements. The spindle MTBF can be determined as the bearing, which is the weakest part of the spindle.

4. Bearings monitoring development

A real-time monitoring device is required for the high-speed spindle to ensure any abnormal bearings revolution conditions are detected. Some researchers have considered placing a vibration unit outside the spindle, and although this works, it is not an optimal solution. The operator may need to be made aware once the abnormal bearing motion conditions. A direct monitoring unit placed in front of the bearing has been proposed, as shown in Fig. 10, where, A is the spindle bearing and sensor ring assembly, and B is the sensor inserted into the space ring, as indicated in Fig 11. There are four sensors at every 90 degrees, which can monitor any abnormal bearing motion, and both sides of the spacer ring are provided with four sensors, which allow both bearings to be monitored whenever the spindle is rotating. When the pressure to the sensor is out of balance, the sensor obtains different data to that while the bearing outer ring is out of balance, which enables the sensor and differential amplifiers to be active and a real-time monitoring to take place.

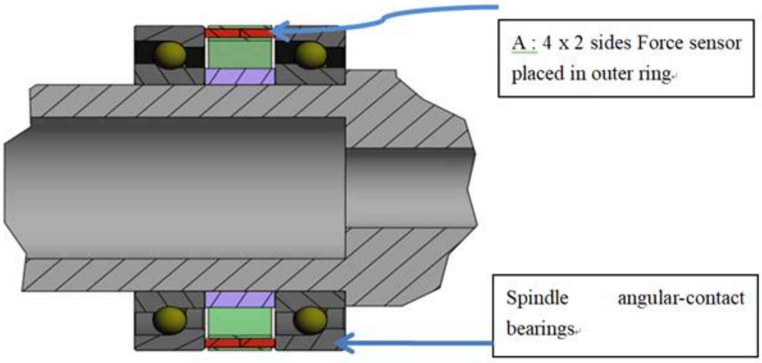


Fig. 10 Spindle bearings with force sensor assembly

Fig. 12 shows all the applied components, where B indicates the PZT force sensor, which is a highly sensitive. The sensitivity is -4pC/N, with 4 pcs placed st every 90 degrees of the ring, and both sides of the rings are provided with the same unit to enable a real-time monitoring function. B is the sensor and C is the holding ring placed between both angular contact bearings, while the holding ring is also applied as a spacer.

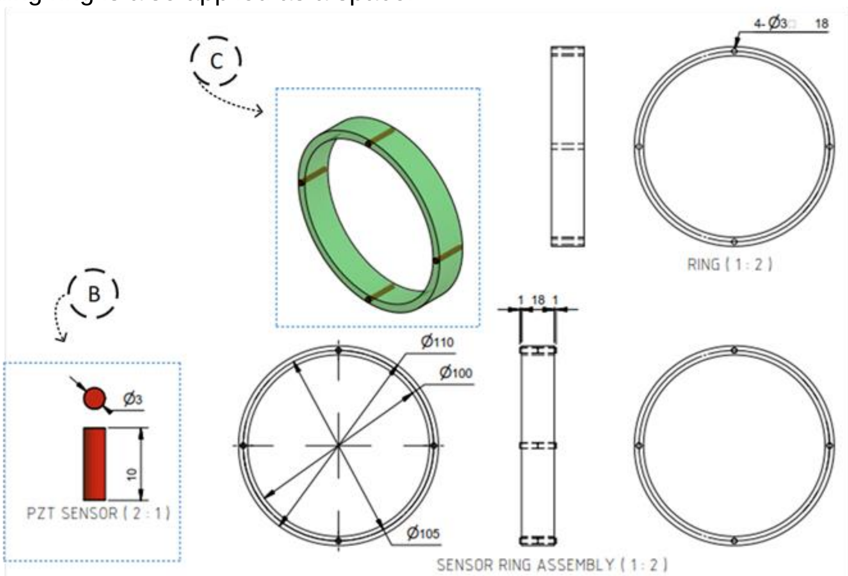


Fig. 11 Holding ring and sensor

The equivalent circuit of a piezoelectric sensor measuring system is illustrated in Fig.12, which shows that the system includes a piezoelectric sensor, sensing cable, and charge amplifier. The cable loading effect is neglected due to the unique properties of charge amplifier. The gain of the overall system can be regarded as consisting of two stages, sensor and charge amplifier stage, with gains of H_{piezo} and H_{amp}, respectively. The gain of each stage is described in the following section, operating under the following conditions.

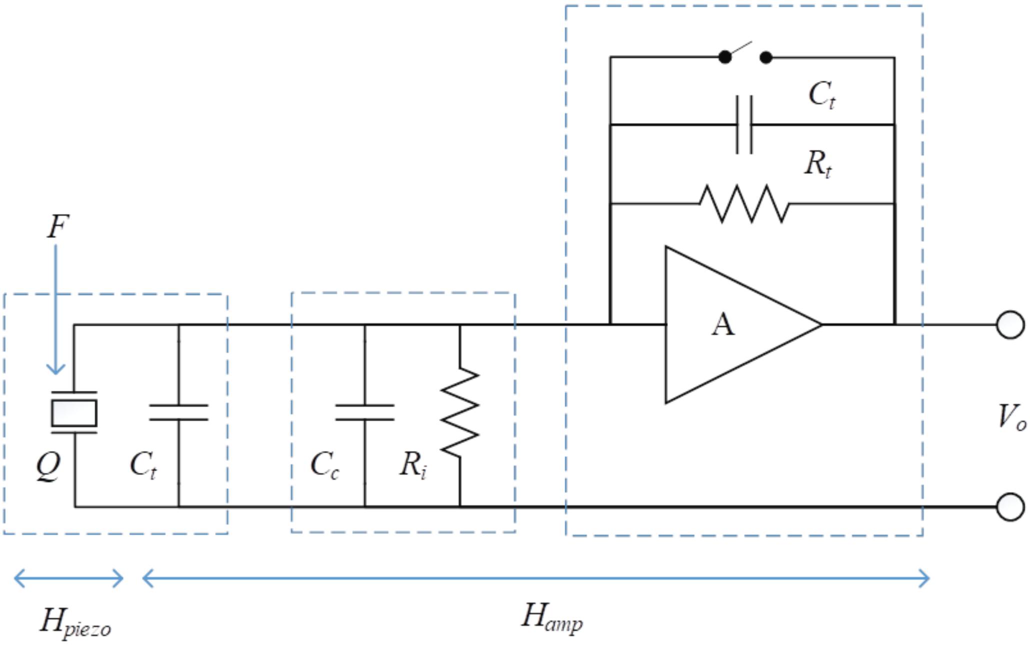


Fig. 12 Simplified circuit diagram of charge amplifier with piezoelectric sensor

1) Gain H_{piezo} and the charge/force property of piezoelectric sensor

The property of piezoelectric material can be represented by the constitutive equation in the IEEE Standard on Piezoelectricity, 1987. ANSI/IEEE. Std._176). The piezoelectric material includes two applications, sensor and actuator. In the sensor application, the external voltage field is zero, and the sensor is exposed to an external force. The constitutive equation can be written as $D = d^d\sigma$. Assume that there is one directional force acting on a stressed material with a cross-section area A, then the vector $\boldsymbol{D}$ of size $(1/3)$ can be simplified to a scalar equation, as shown in equation (7), which describes the relationship between stress and electric displacement. As the force stress is applied to the piezoelectric material, electric displacement is induced. Furthermore, total charge is described in equation (8), where the total charge amount is proportional to the electric displacement D and piezoelectric coefficient d.

$$D = d\sigma \tag{7}$$

$$Q = \int D\,\mathrm{d}A, \tag{8}$$

where:

D: Electric displacement [Coulomb/m^2]

d: Piezoelectric coefficient, sensitivity of force to charge [Coulomb/Newton]

σ: Stress acting on material [Newton/m^2]

Q: Induced charge [Coulomb]

Combining (7) and (8), the overall force to charge response is represented as (9).

$$Q = Dd\sigma = dF \tag{9}$$

Hence, in the first stage, the gain becomes

$$H_{piezo} = \frac{Q}{F} = d, \tag{10}$$

The sensor manufacturer's datasheet describes the piezoelectric coefficient d, for a typical piezoelectric sensor. Normally, the piezoelectric coefficient (or sensitivity) ranges is from several to tens of pC. For example, Fig. 13 shows that the sensor sensitivity is -4 pC/N over a wide measuring force range, and a linear feature meets the requirement of monitoring application.

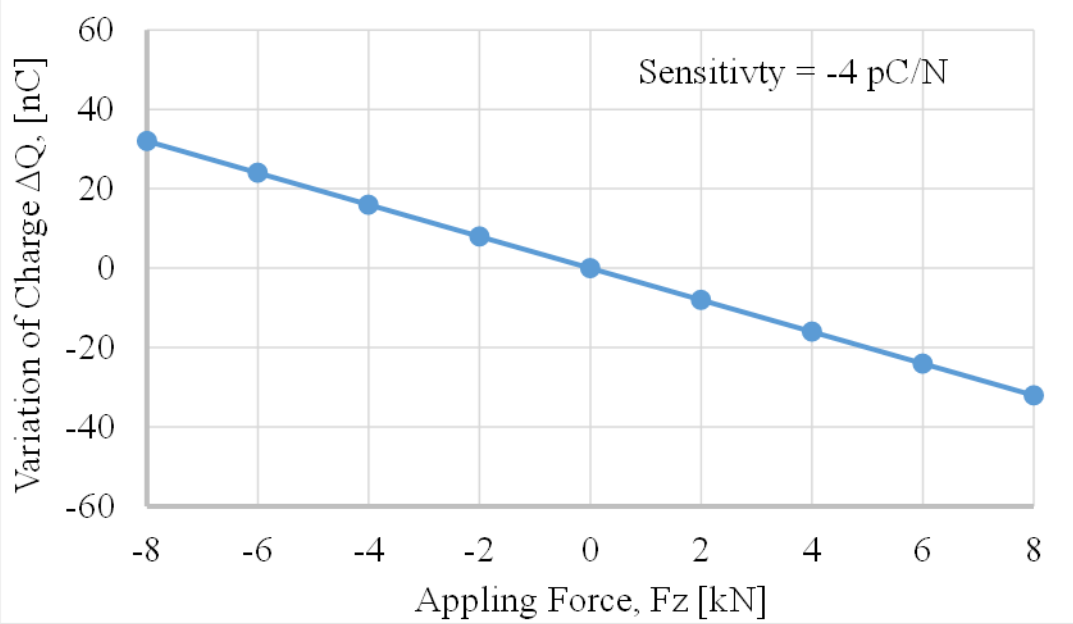


Fig. 13 Characteristics of piezoelectric force sensor, an example for sensitivity of -4 pC/N

a) Signal conditioning of piezoelectric sensor V/Q

Because the piezoelectric sensor has very high output impendence and the general measuring device only has input impendence in the order of several MΩ, the loading effect is an issue for piezoelectric measuring devices. For example, the input impendence of an oscilloscope and data recording device is 1 MΩ. The charge amplifier offers an advantage in term of signal conditioning of the piezoelectric sensor. As mentioned previously, the stray capacitor of the cable is regardless.

In the second stage, the gain is

$$H_{amp}(S) = \frac{V_o}{Q} = \frac{-1}{C_g}\frac{sT_t}{1+sT_t}, T_t = R_t C_t, \tag{11}$$

The circuit is a high-pass filter, and in (11), once the measuring frequency is very close to quasi-static frequency, the output voltage quickly decreases to zero. The high time constant T_t enhances the 3dB frequency to be as close as possible to quasi-static frequency, however, the large C_g is significant for eliminating circuit sensitivity, which is the gain H_{amp}. In term of the time domain, as the charge Q is applied to the piezoelectric sensor, the output voltage of the amplifier decays and it performs like a $R_t C_t$ -circuit characteristic with a finite time constant, T_t . As a result, if only the capacitor-resistor combination is considered, it is the challenging foe the conventional charge amplifier to achieve pure static or quasi-static measurement.

To overcome the aforementioned problem, a reset switch M1 is connected in parallel to the charge amplifier circuit, as shown in Fig. 14, where M1 is used to reset the charge in the capacitor, C_t. As the amplifier input is applied with voltage, while the switch M1 is on, the capacitor C_g is rapidly discharged. After the switch M1 is turned off, the amplifier performs as though a force is simply applied to the piezoelectric element. The coordination of an additional analogue/digital converter (ADC) and digital signal processing unit is required for data sampling, processing and digital/analogue filtering, and this function is implemented and founded in commercial charge amplifiers and/or instruments. The appropriate range of input charge and output voltage of the commercial amplifier can be found in the instrument manual. In the second stage of the signal condition, the circuit becomes

$$H_{amp}(s) = \frac{V_o}{Q} = H_{ins} \tag{12}$$

where H_{ins} also represents the charge sensitivity of the amplifier. Notably, the frequency response term is shown in (12), and is based on the performance of the M1 resetting time, data sampling rate, processing unit, and bandwidth of the external digital/analogue filter.

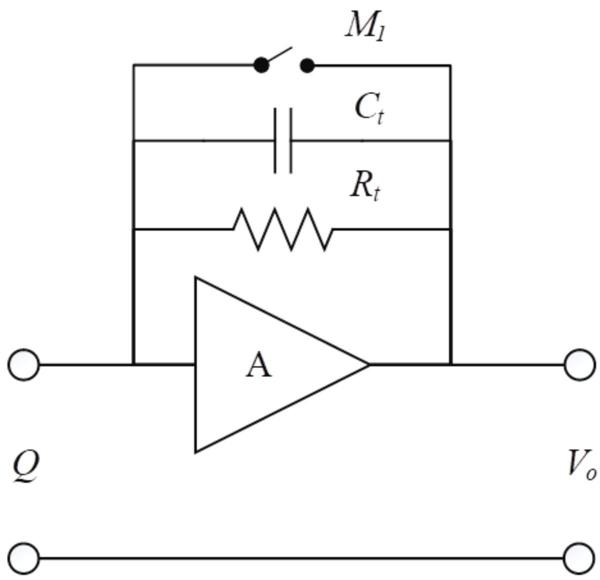


Fig 14 Improved charge amplifier

A) Voltage gain of overall circuit

The voltage gain of the circuit, as illustrated in Fig 14 can be reset switching M1, and becomes

$$H_o(s) = H_{piezo} H_{amp} \tag{13}$$

Fig. 15 shows the Bode diagram, where a linear output is obtained, if it is confirmed that the charge amplifier produces a perfect output.

Fig. 15 Charge amplifier simulation

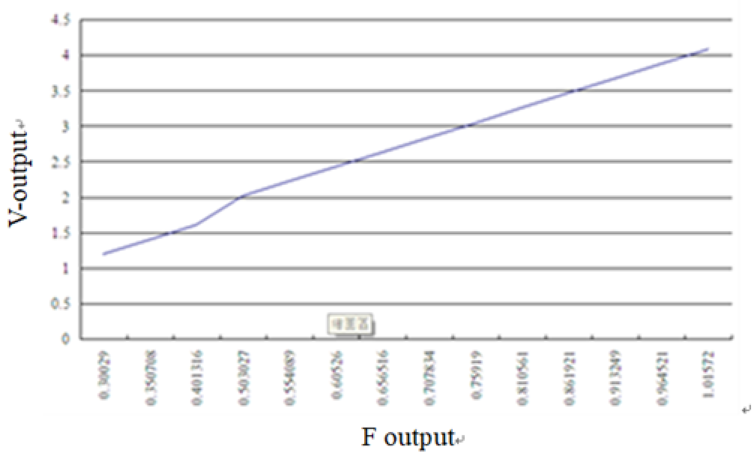


Fig. 15 Charge amplifier simulation

Two groups of data provide precise output from the sensor, which is monitored from both front angular contact bearings. In the case where the bearing is out of balance in its rotation, in either the axial direction or radial direction, the force sensor can detect the motion, and the charge amplifier acts as a data filter to enlarge the scale, which allow the second stage of data amplification unit to act as a controller to declare whether the bearing has reached the level to be inspected.

The design of the proposed sensing system is shown in Fig. 16, and is composed of the sensor, charge amplifier, and differential amplifier stages.

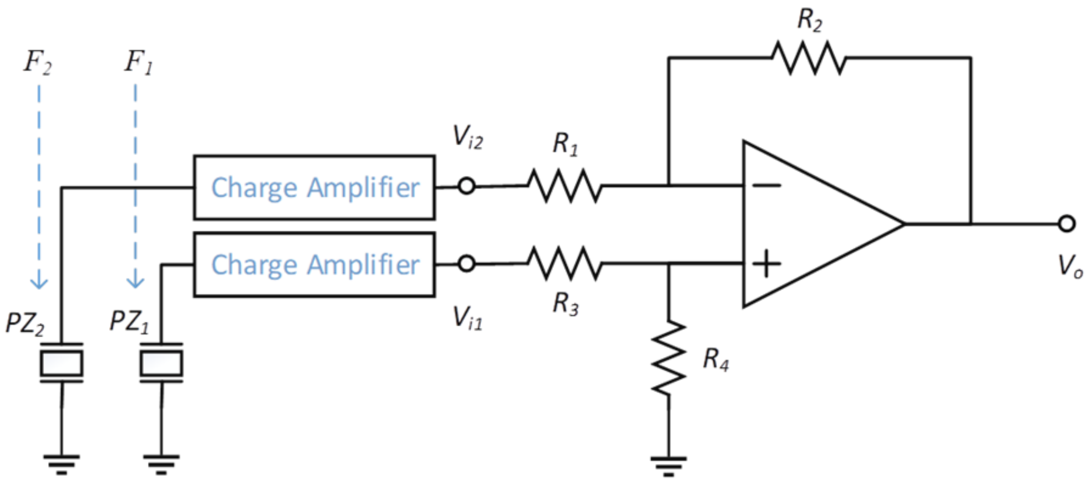


Fig. 16 Differential amplifier as second stage

(3) Fig. 17 shows the Bode diagram, with its response of output voltage from the charge amplifier. It is clear that the output is stable, which provides high sensitively feed-back to the CPU for the compensation, or an error message is provided to the equipment operator, without any timing delay, indicating that the amplifier is effective for the application.

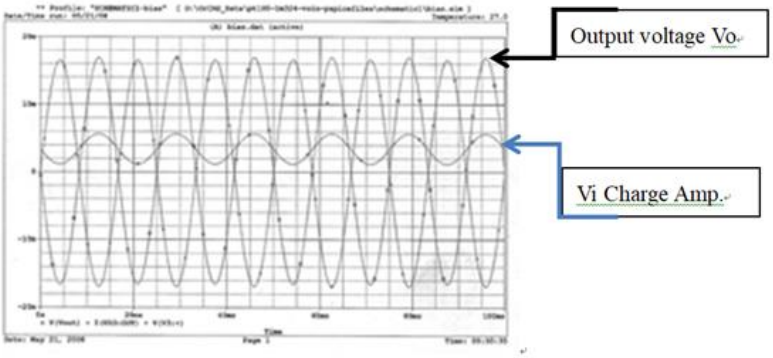


Fig. 17 Simulation of differential amplifier

IV Experiment

Fig.18 shows the real-time data output from the monitoring system. Spindle vibration monitoring has been discussed in previously.〔8〕 It is important that this system be applied and to detect whether the spindle is out of balance. Under normal conditions, the spindle run for months without any problems, except for corrosion occurring. While the output of the differential amplifier is stable, the spindle thermal extension becomes stable, 10-15 minutes after the spindle start-up, Fig 19 shows, it is confirmed that this research meets the requirement, as the data is obtained while the monitoring unit is operates.

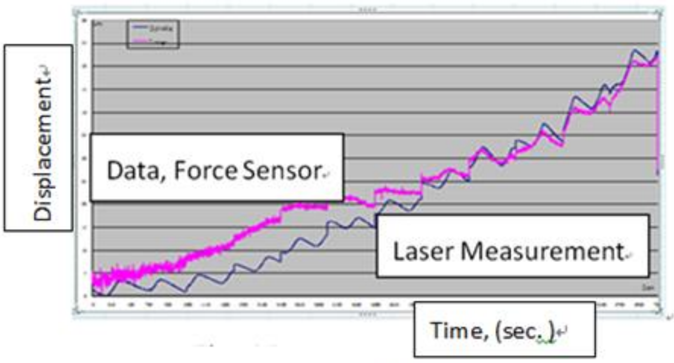


Fig. 18 Laser measurement report

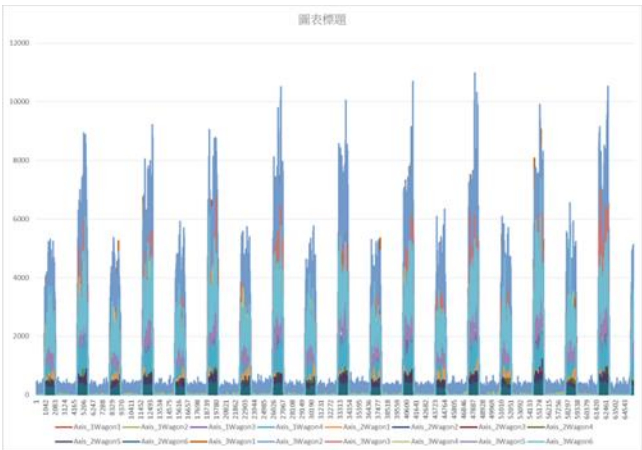


Fig 19 Force sensor monitoring output (8 channels)

Conclusion

Bearing treatment is considered to be major factor of spindle life, and a bearing set-up study and simulation was conducted. A direct monitoring system was developed, and the simulation confirmed its functioning, while the experiment proved that the system operates precisely. The aim of this research is to support the requirements for any high-speed spindle to adapting the requirement of the fourth industrial revolution equipment. Prior notice is available, which can provide information before failure occurs. A perfect after-sales service can be provided instead of the equipment remaining dead for a few days to months, thereby meeting the requirements for Industries 4.0.

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