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Performance Complexity Measurement of Tightening Equipment Based on Kolmogorov Entropy

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Abstract**—**The performance of the tightening equipment will decline with the working process in manufacturing system. The main manifestations are the randomness and discretization degree increasing of the tightening performance. To evaluate the degradation tendency of the tightening performance accurately, a complexity measurement approach based on Kolmogorov entropy is presented. At first, the states of performance index are divided for calibrating the discrete degree. Then the complexity measurement model based on Kolmogorov entropy is built. The model describes the performance degradation tendency of tightening equipment quantitatively. At last, a study case is applied for verifying the efficiency and validity of the approach. The research achievement shows that the presented complexity measurement can effectively evaluate the degradation tendency of the tightening equipment. It can provide theoretical basis for preventive maintenance and life prediction of equipment.

Keywords**—**Complexity measurement, Kolmogorov entropy, manufacturing system, performance evaluation, tightening equipment.

I. Introduction

THE instability and suddenness of equipment's fault is a research focus in manufacturing system, especially in the aspect of the performance evaluation and life prediction [1]-[3]. It is not only related to the economic loss of production, but also the threat to the safety of staff. As a kind of complicated production phenomenon, the performance degradation and failure of mechanical equipment are manifested as inhomogeneity, difference, diversity and randomness. Meanwhile, the increasing complexity, flexibility, and intelligence have proposed great challenge for the performance evaluation and the maintenance strategy formulation.

To the efficiency of the manufacturing system and its safety and stability paying attention to the stability of manufacturing equipment's performance under normal operating conditions is more valuable, comparing with the equipment performance evaluation on the fault condition of the equipment. With the development of systematization, network and intelligence, it is imperative to carry out the state inspection and performance evaluation of key equipment components. Among them, the tightening equipment is an important unit in manufacturing system. The key indexes of its performance are usually tightening torque and tightening angle which are related to the quality of the engine and other products directly. Hence it is of great significance to research the performance evaluation of tightening equipment.

This paper demonstrates an approach which is used to evaluate the performance degradation tendency based on complexity measurement especially the Kolmogorov entropy. The structure of this work is essentially in four parts. Firstly, the related work literature for performance evaluation and complexity measurement is primarily presented in Section II. In the following section, an approach based on Kolmogorov entropy is presnted to measure and quantifies the performance complexity used in evaluating the performance degradation tendency of tightening equipment. Then, a detailed description of the approach is introduced in Section III, after which the application of the method to a tightening machine is provided for verifying the validity of the approach in Section IV. Finally, conclusions appear in Section V.

II. Related Works

In the field of performance evaluation, many researchers have completed a lot of work. Pan et al. [4] measure the complexity changes of the rolling element bearing by two nonlinear methods: Correlation dimension and approximate entropy. The performance degradation process of rolling element bearing has been studied based on simulation and bearing accelerated life test data. Sadok et al. [5], [6] study a closed loop manufacturing system to establish an optimal production control which minimizes the sum of inventory, transportation, lost sales and maintenance costs taking into account the degradation of the machines and the transport vehicle. And for the performance evaluation of the system, they study the impact of degradations costs on the optimal manufacturing inventory. Considering the influence of working conditions on reliability, Li et al. [7] evaluate the reliability of NC machine tools using Cox proportional hazards model to describe the relationship between the working condition covariance and the reliability level of NC machine tools. Based on the life cycle cost, the equipment availability and the overall efficiency of the equipment, Lad et al. [8] establish a reliability evaluation model of CNC grinding machine, which provides theoretical guidance for the optimal configuration selection and equipment maintenance of the machine. Lv et al. [9] study the impact of system configuration on performance with respect to reliability, scalability, convertibility, quality, productivity and cost using manufacturing system engineering theory, Boolean algebra, probability statistics theory, stream of variation methodology and so on. Zhang et al. [10] construct the screw vibration signal feature vectors by compressing the feature data with principal component analysis method. And they propose

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the screw performance degradation assessment model based on quantum genetic algorithm and grey neural network. Zhou et al. [11] propose a multi-state reliability modeling method in a maintenance cycle based on the performance degradation by using the analysis method from machine to system. Furthermore, the reliability analysis method of performance degradation due to the aging is derived.

In the existing research results, the equipment evaluation mechanism is only to evaluate the status of the equipment itself. It is hard to reflect the ability to maintain the current state of equipment. It is necessary to evaluate the performance of mechanical equipment from the point of view of the uncertainty of process quality, thus providing the theoretical basis for the equipment maintenance strategy formulation.

Complexity theory is an effective method to describe the randomness and uncertainty, which provides a new idea for the performance evaluation of mechanical equipment. Complexity is mainly from the statistical significance, emphasizing the connection with randomness or disorder. The mathematical methods used to describe the complexity mainly include information entropy, Kolmogorov entropy, Lyapunov exponent, Lempel-Ziv algorithm, etc. [12] Yan et al. [13] present a machine health evaluation technique using the Lempel-Ziv complexity as a numerical measure. The presented approach is thus suited for the condition monitoring of machine systems under varying operation and loading conditions. According to the analysis of chaos identity and the correlation dimension and Kolmogorov entropy of some engine, Yu et al. [14] propose a new method of fault diagnosis that integrated correlation dimension with Kolmogorov entropy. The method shows that the different fault has different correlation dimension and Kolmogorov entropy because of their different kinetics mechanisms, and thus correlation dimension and Kolmogorov entropy can be used to identify the fault symptoms. Yan et al. [15] present a non-linear time series analysis technique for machine health monitoring, based on the complexity measure. Numerical simulation of an analytic signal is presented to quantitatively establish the relationship between the severity of signal degradation and the complexity values for quantifying the randomness or regularity of a time series. Dong et al. [16] propose a degradation analysis method based on the complexity which is calculated by Lempel-Ziv algorithm for evaluating the degradation tendency of machine tool's spindle systems. Efthymiou et al. [17] measure the unpredictability of manufacturing system by Lempel-Ziv algorithm, and study the fluctuation of manufacturing performance index to assess the complexity of manufacturing system.

So far, several approaches have been taken in order to evaluate the performance of the equipment. But only few authors consider the quality of the operation and use the qualified data instead of failure rate to assess the complexity of tightening equipment. Therefore, within the normal operating range, measuring equipment performance degradation tendency is the main objective of this paper.

III. Performance Measurement of Tightening Equipment Based on Kolmogorov Entropy

A. Problem Description

The key indexes to evaluate the performance of the tightening equipment are tightening torque and tightening angle, which relate to the assembly quality of products. With the increase of the times which the tightening equipment is used, the performance will have a recession in the working process. The characteristic is the fluctuation of torque and angle. And the scope of the volatility gradually expanded, the accuracy decreased, etc. It also directly leads to the instability of the assembly quality.

In order to reflect the complexity of equipment, Kolmogorov entropy is used to measure the complexity of performance. And the measurement and comparison of torque and angle are carried out.

B. State Division of Performance Index for Tightening Equipment

The key to computing the performance complexity of equipment is to define the operating states of the equipment. Under normal conditions, the operating states can be divided according to the operating status of equipment (such as voltage, temperature, sound, vibration). The product processing quality and assembly precision can also be used to define the states of the equipment. Hence a fraction of the tightening data can be selected as a sample for the relevant state division and calibration. The data of selected samples are supposed to be valid. If the data is not valid (from failure equipment), there is no need to measure it. Finally, the torque and angle are selected as the index to describe the performance. It is different from the method using failure rate and other indicators to measure the performance of the equipment which can only be judged from whether the operation is normal or not. In order to measure the performance of equipment by the fluctuation of the qualified data, this method can be more accurate to reflect the influence of equipment performance degradation on the quality of products.

To divide the states of performance, the data is divided into m states in a day. The state i in day d is represented by S_{id}.

$$\begin{cases} S_{1d}: F_{sd} - b \le F_{id} \le F_{sd} + b \\ S_{2d}: F_{sd} - 2b \le F_{id} \le F_{sd} - b, F_{sd} + b \le F_{id} \le F_{sd} + 2b \\ \cdots \\ S_{id}: F_{sd} - 3b \le F_{id} \le F_{sd} - 2b, F_{sd} + 2b \le F_{id} \le F_{sd} + 3b \\ \cdots \\ S_{md}: F_{sd} - mb \le F_{id} \le F_{sd} - (m-1)b, \\ \quad F_{sd} + (m-1)b \le F_{id} \le F_{sd} + mb \end{cases} \tag{1}$$

where, the torque output value of the tightening equipment is F_{sd}, b is the span value of states. F_{id} is the measurement value of torque. S_{md} is determined by the upper and lower bounds of the sample data.

C. Performance Complexity Model for Tightening Equipment

Discrete information sources can be described by dimensional discrete random variables, denoted as *X*. It is described as the set $\{x_1, x_2, \cdots, x_i, \cdots, x_n\}$. The probability of the variable x_i is $p(x_i)$. The entropy of the discrete information sources is *H*(*X*).

$$H(X) = -\sum_{i=1}^{n} p(x_i) \log p(x_i) \tag{2}$$

H(*X*) represents the quantity of the uncertainty of the system *X*. Only the expected state of the manufacturing equipment is considered when measuring the static complexity. Dynamic complexity is concerned with the actual state of manufacturing equipment in the process of operation.

The tendency of the performance is shown in Fig. 1. *d* presents the work time the units of which are in days. *m* is the number of the divided states. *k* describes the change of the states along with the work time.

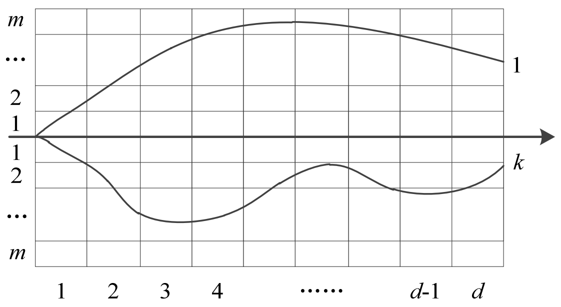

Fig. 1 Different state paths for the diffusion of the states

The data are divided into *m* states in a day. The state set in the day *d* is represented by Y_d.

$$Y_d = \{S_{1d}, S_{2d}, \cdots, S_{md}\} \tag{3}$$

where, S_{md} is the *m* state in the day *d*.

The probability of every state is shown by P_d as:

$$P_d = \{p_{1d}, p_{2d}, \cdots, p_{md}\} \tag{4}$$

where, p_{md} is the probability of the state *m* in the day *d*.

There are m^d state paths in the time sequence. The probability of state path *k* is $P_{kd}(m1, m2, \cdots, md)$. There are m^d state paths.

$$P_{kd}(m1, m2, \cdots, md) = \prod_{e=1}^{d} p_{me} \tag{5}$$

where, p_{me} is the probability of the state *m* in the day *e*.

The performance complexity of the tightening equipment in all the *d* days is H_d.

$$H_d = \sum_{k=1}^{m^d} P_{kd}(m1, m2, \cdots, md) \log_2 \frac{1}{P_{kd}(m1, m2, \cdots, md)} \tag{6}$$

The value of Kolmogorov entropy of the tightening machine in the day *d* is K_d.

$$K_d = H_d - H_{d-1} \tag{7}$$

A certain amount of additional information is needed to depict the change of status from one day to the next day. K_d is the Kolmogorov entropy which equals to the additional information value from the day *d*-1 to day *d*. The randomness or disorder increase with the result, and the amount of information contained in it reflect the stability of the equipment performance. That is to say, if the process is chaotic and random, the performance is more uncertain. The increasing amount of information means that the tendency of performance degradation is severe. So K_d is able to evaluate the performance tendency of the tightening equipment.

IV. Case Study

In the production line of a large clutch production enterprise, there are many tightening equipment which are responsible for multiple tightening operations in the production process. All tightening devices are equipped with real-time monitoring of torque and angle. So the torque and angle can be chosen for performance complexity measurement.

A. The Sample

The tightening device is selected the torque setting value of which is $58\,\text{Nm} \pm 5\,\text{Nm}$, the range of torque is 58.0 Nm to 58.8 Nm. The length of the sample is 92 days. The interval data of 14 days is collected once a week. All of the torque data is divided into four state intervals as:

$$\begin{cases} S1: 58.0\,\text{Nm} \le F < 58.2\,\text{Nm} \\ S2: 58.2\,\text{Nm} \le F < 58.4\,\text{Nm} \\ S3: 58.4\,\text{Nm} \le F < 58.6\,\text{Nm} \\ S4: 58.6\,\text{Nm} \le F < 58.8\,\text{Nm} \end{cases}$$

All the data obtained are partitioned by day. The state probability distribution of torque state is as shown in Table I. Fig. 2 shows the probability distribution sequence of torque state these days. The data of tightening equipment is divided into four states. The discretization degree of the state increases with the work time.

Obviously, a fraction of measurement data transfers from S1 to S2 and S3. Probability of S1 reduces from 92.38% to 60.38%. The probability of S2 and S3 all increase obviously. The degree of discretization of the tightening quality increases. More information is needed to describe the status of the device.

The angle data of the same sample also needs to be measured in order that the degradation trend of the overall performance of the device could be analyzed. The data is taken from the same tightening device in the same experimental time. The range of angle is from 40 degrees to 70 degrees.

TABLE I
PROBABILITY DISTRIBUTION OF TORQUE STATE

Day \ States	S1	S2	S3	S4
1	0.923810	0.076171	0.000019	0.000000
8	0.927638	0.030151	0.042211	0.000000
15	0.863529	0.117647	0.018824	0.000000
22	0.833333	0.148333	0.011890	0.006444
29	0.841468	0.125651	0.025335	0.007546
36	0.866885	0.116065	0.013804	0.003246
43	0.869756	0.108048	0.014652	0.007544
50	0.833442	0.128762	0.024375	0.013421
57	0.788329	0.139244	0.051441	0.020986
64	0.778688	0.147377	0.051344	0.022591
71	0.782926	0.167579	0.035947	0.013548
78	0.699085	0.202742	0.075401	0.022772
85	0.708571	0.238571	0.037142	0.015716
92	0.647008	0.251709	0.071282	0.030001

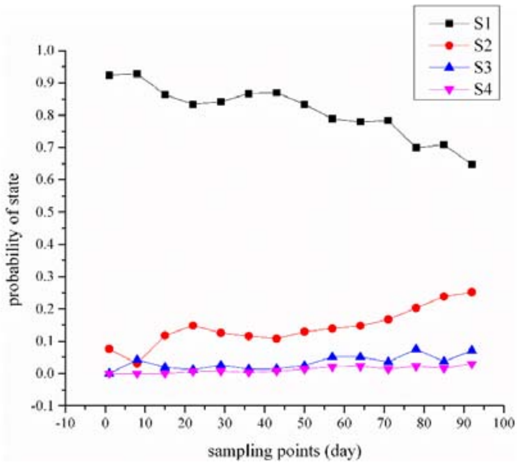

Fig. 2 The probability distribution sequence of the toque state

TABLE II
PROBABILITY DISTRIBUTION OF ANGLE STATE

Day \ States	S1	S2	S3	S4
1	0.941401	0.037060	0.021540	0.000000
8	0.920312	0.036372	0.028326	0.014991
15	0.896080	0.058240	0.025425	0.020256
22	0.893536	0.058156	0.032016	0.016292
29	0.932033	0.030175	0.020236	0.017556
36	0.896624	0.081155	0.012132	0.010089
43	0.791224	0.110333	0.064456	0.033987
50	0.843152	0.081543	0.062032	0.013273
57	0.798887	0.120763	0.060254	0.020096
64	0.847641	0.081625	0.032156	0.038578
71	0.738041	0.124512	0.085216	0.052231
78	0.662708	0.187479	0.103752	0.046061
85	0.687418	0.139582	0.102396	0.070604
92	0.711479	0.141202	0.081602	0.065716

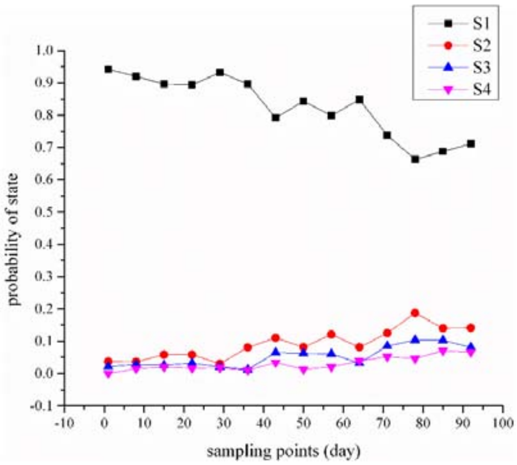

Fig. 3 The probability distribution sequence of the angle state

$$\begin{cases} X_1 : 40^{\circ} \leq A < 47.5^{\circ} \\ X_2 : 47.5^{\circ} \leq A < 55^{\circ} \\ X_3 : 55^{\circ} \leq A < 62.5^{\circ} \\ X_4 : 62.5^{\circ} \leq A < 70^{\circ} \end{cases}$$

The probability distribution of angle state is shown in Table II. Fig. 3 shows the probability distribution sequence of angle state.

B. Complexity Measurement of the Sample

The complexity of torque and angle is calculated by the performance complexity measurement model for tightening equipment in Section III. The results are shown in Table III. The complexity values of torque and angle are analyzed together. It can be easier to observe the situation of equipment performance changes as shown in Fig. 4.

TABLE III
COMPLEXITY OF TORQUE AND ANGLE

Day \ Complexity	Complexity of Torque (bit)	Complexity of Angle (bit)
1	0.3889	0.3775
8	1.2800	1.0412
15	4.2845	1.2588
22	6.0040	1.2790
29	6.1848	0.9266
36	5.2111	1.1587
43	5.3154	2.0779
50	6.5114	1.6679
57	8.0300	1.9692
64	8.2528	1.6756
71	7.7187	2.4457
78	9.8656	2.7797
85	8.9288	2.7498
92	10.6459	2.6026

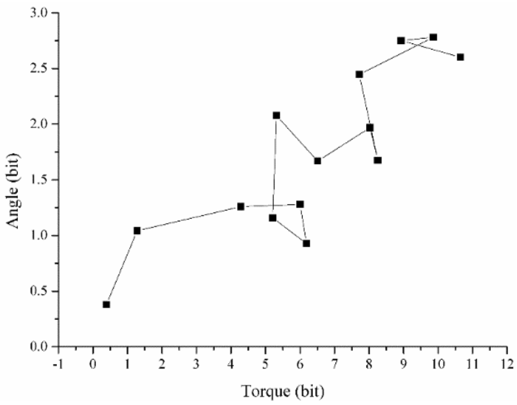

Fig. 4 The complexity of torque and angle

C. Discussion

The angle data and torque data of the same sample time depict the degradation of the tightening equipment. The results show that the performance degradation gradually increases with the increase of the running time of the equipment. However, the degradation of torque performance is faster than that of the angle.

The measurement approach of tightening equipment performance complexity based on torque and angle data is complementary to each other. It can describe the degradation tendency of the tightening equipment in two dimensions: the degree of random fluctuation and the degree of disorder.

V. Conclusion and Future Work

A new performance complexity model of tightening equipment is built considering the angle index and torque index simultaneously. The model is proposed to describe the degradation tendency of tightening equipment based on Kolmogorov entropy. And the discrete degree of performance index is fully considered by its states division. The accuracy and the effectiveness of the represented approach were confirmed through the case study. The results have validated that the proposed complexity measurement approach applies to evaluate the degradation tendency of the tightening equipment.

In continuative research activities, the performance prediction should be incorporate with the performance evaluation approach which was proposed in this paper. Furthermore, life estimation of the tightening equipment should be taken into account. It will be meaningful for maintenance of the tightening equipment.

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