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Research Article

Information Mining for Friction Torque of Rolling Bearing for Space Applications Using Chaotic Theory

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Abstract: Information on the friction torque time series of rolling bearings for space applications is mined to reveal its intrinsic operative mechanism of nonlinear dynamics. Based on the chaos theory and the simulation experiment of the changing vacuum, this study studies the changing characteristic of the friction torque with the decreasing vacuum in physical space, investigates variety and complexity forms of the strange attractor of the friction torque in phase space and estimates the maximum Lyapunov exponent and the correlation dimension. As a result, the intrinsic operative mechanism of nonlinear dynamics of the rolling bearing friction torque is characterized by a nonlinear and non-monotonic trend of the estimated correlation dimension with the increasing mean of the friction torque.

Keywords: Chaotic theory, friction torque, information mining, rolling bearing, space applications

INTRODUCTION

Spacecrafts move in earth orbit commonly under the vacuum condition at the 1×10^4-1.33×10^7 Pa air pressure for many scientific experiments. As a major performance indicator, the friction torque of rolling bearings is required strictly to ensure the good performances of spacecrafts (Xia and Li, 2011). Therefore, it has been given the attention continuously along with many new findings.

For example, Wikstrom and Hoglund *et al*. (1996a, b) investigated the starting and steady-state friction torque of grease-lubricated rolling bearings at low temperatures; Xia and Wang (2009) studied the grey relation of the nonlinear characteristic with the dynamic uncertainty of the rolling bearing friction torque; and Cousseau *et al*. (2010) presented an experimental measuring procedure for the friction torque in rolling bearings and quantified the power loss and the heat evacuation for each lubricant tested via continuously monitoring the friction torque and operating temperatures. But, the existing findings do not involve the characteristics of the rolling bearing friction torque with changing vacuum.

For rolling bearings for space applications, it is possible that different vacuum environments lead to different states of the values of the friction torque (Xia and Wang, 2011; Xia, 2012), in which a wealth of information should be implied and it must be extracted for safe reliable operation of spacecrafts. For this reason, based on the chaotic theory and the simulation experiment of the change vacuum, information mining for the friction torque time series of rolling bearings for space applications is made to reveal its intrinsic operative mechanism of nonlinear dynamics.

EXPERIMENT OF ROLLING BEARING FRICTION TORQUE

Vacuum is a gas condition, under which in the given space, the pressure is lower than 101325Pa, viz., one standard atmospheric pressure and it is defined as:

$$\text{Vacuum} = \text{atmospheric pressure} - \text{absolute pressure} \quad (1)$$

Over the Earth, the higher the altitude is, the thinner the air is and the higher the vacuum is.

The simulation experiment is produced and the indirect measuring method is used. The testing system consists of a direct current stabilized source, a vacuum tester and a reaction flywheel control box, etc. The rolling bearing is installed in a vacuum housing on the vacuum tester for mimicking a space environment. The friction torque is expressed as the electric current X, in mA. The vacuum is expressed as the vacuum factor v which is a dimensionless variable and takes values in the range from 0 to 1. The higher the vacuum is, the smaller the vacuum factor is; otherwise, the larger the vacuum factor is. The experimental condition is listed in Table 1. The friction torque of six rolling bearings, numbered as 1, 2, 3, 4, 5 and 6, respectively, is measured in the

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Table 1: Experimental condition

Parameter	Parameter value
Vacuum factor, v	0-1
Temperature, T/°C	20-25
Relative humidity, R/%	55
Sequence number of rolling bearing	1-6
Rotational speed (six rolling bearings), w/(r/min)	5140-5037(No.1), 4635-4610(No.2), 4735-4710(No.3), 4761-4720(No.4), 4804-4736(No.5), 4661-4619(No.6)
Sample interval, Δt/h	24

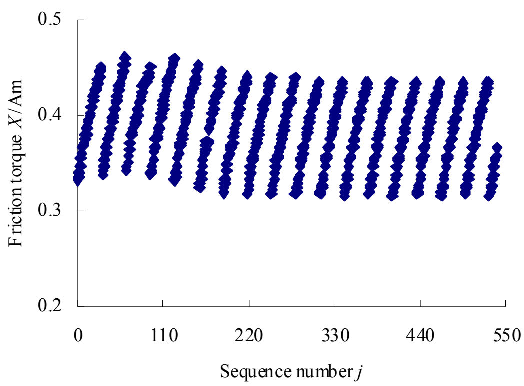

Fig. 1: Time series of friction torque of rolling bearing 1

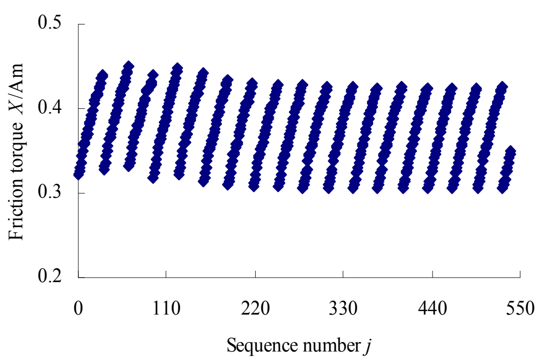

Fig. 2: Time series of friction torque of rolling bearing 2

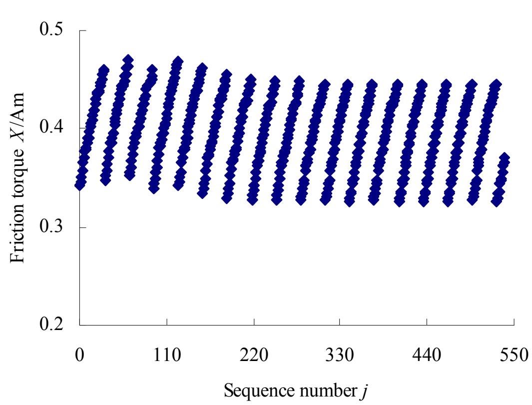

Fig. 3: Time series of friction torque of rolling bearing 3

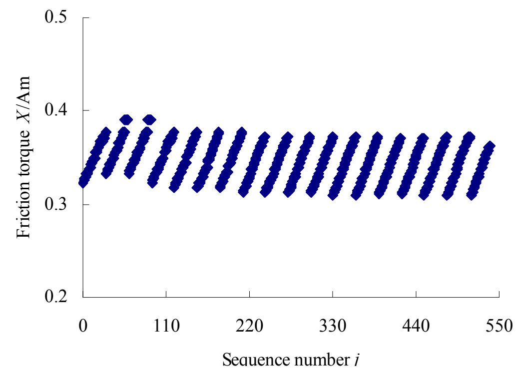

Fig. 4: Time series of friction torque of rolling bearing 4

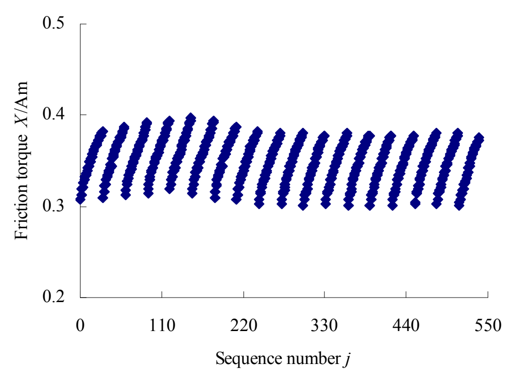

Fig. 5: Time series of friction torque of rolling bearing 5

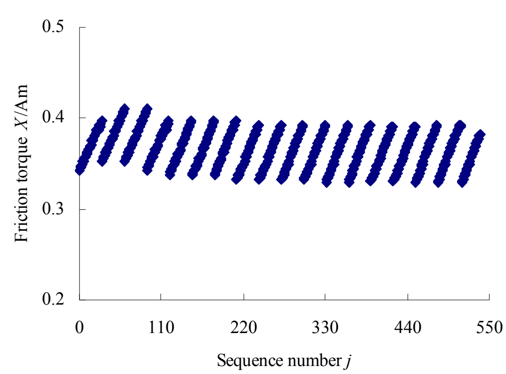

Fig. 6: Time series of friction torque of rolling bearing 6

experimental investigation and the time series of the test data are shown in Fig. 1 to 6.

In the experimental investigation the vacuum factor v is changed linearly from 0 to 1 one period every about 30 days in order to simulate the changing vacuum. This results in the regularly linear increase of the time series of the rolling bearing friction torque. Based on the chaos theory, this study aims at discovering the intrinsic operative mechanism of nonlinear dynamics of the friction torque of the rolling bearing that runs in changing vacuum.

INFORMATION MINING FOR EVOLUTION OF ROLLING BEARING FRICTION TORQUE

Time series: Assume the time series of the friction torque of rolling bearings for space applications in Fig. 1 to 6 can be expressed as:

$$X = (x(1)), x(2), \ldots, x(j), \ldots, (J) \tag{2}$$

where,

X = The time series of the friction torque of rolling bearings for space applications
j = The sequence number
$x(j)$ = The jth datum in
X and J = The number of the data in X

Mean: Via the statistical theory, the mean of the rolling bearing friction torque is defined as:

$$X_0 = \frac{1}{J}\sum_{j=1}^{J} x(j) \tag{3}$$

where, X_0 = The mean of X.

The mean can be employed to make information mining for the measure of the rolling bearing friction torque in physical space.

Phase trajectory: According to the phase space reconstruction theory, a phase trajectory can be obtained as:

$$\mathbf{X}(t) = (x(t), x(t+\tau), \ldots, x(t+(k-1)\tau), \ldots, x(t+(m-1)\tau)); \quad t = 1,2,\ldots,M; k = 1,2,\ldots,m \tag{4}$$

with:

$$M = J - (m - 1)\, \tau \tag{5}$$

where, t stands for the $t$he phase trajectory, x $(t+ (m\text{-}1)\tau)$ for the delay value, m for the embedding dimension which is obtained by the false nearest neighbor method (Sofiane *et al*., 2006), τ for the delay time which is obtained by the mutual information method (Gao *et al*., 2008) and M for the number of the phase trajectories.

Equation (4) is the m-dimension state space, viz., the phase space reconstituted by the measured value x (t) and the delay value x $(t+ (m–1)\tau)$.

The phase space reconstruction can lay the foundation for information mining for chaotic characteristics of the rolling bearing friction torque in phase space.

Maximum lyapunov exponent: The first chaotic characteristic of the rolling bearing friction torque as a time series is the maximum Lyapunov exponent.

As for a chaotic system, its sensitive dependence on the initial conditions is that two phase trajectories that have nearly identical initial states will separate from each other at an exponentially increasing rate. Lyapunov exponents are the quantitative measure for distinguishing the chaotic characteristics of the time series. In the practical time series, λ_1, the maximum Lyapunov exponent, is generally estimated to distinguish the characteristics of the time series. If λ_1>0, the time series is the chaotic time series. In this study, the Wolf method (Wolf *et al*., 1985) based on the evolvement method of the phase trajectories is employed to calculate the maximum Lyapunov exponent λ_1 and the average period P is obtained by means of the fast Fourier transform algorithm (Lv *et al*., 2002; Xia, 2012).

In general, the longest prediction time, namely, the predictable time, is defined as $T_m=1/\lambda_1$, at which the state errors of the time series are increasing twice and it can also be regarded as one of the reliability indexes of a short-term prediction.

Strange attractor: The second chaotic characteristic of the rolling bearing friction torque as a time series is the strange attractor.

The strange attractor is a form of the phase trajectory, from which the evolution of the dynamic characteristic of the rolling bearing friction torque can be diagramed in phase space. In this study, the form is defined as a curve with the abscissa x (t) and the ordinate x $(t+ (m\text{-}1)\tau)$ $x(t)$.

Correlation dimension: The third chaotic characteristic of the rolling bearing friction torque as a time series is the correlation dimension.

The correlation dimension in the chaos theory is used to study the nonlinear characteristics of the rolling bearing friction torque.

Let t = i and l, respectively, in Eq. (2), then the distance between two trajectories X (i) and X (l) is obtained as:

$$r(i,l) = \sqrt{\sum_{k=1}^{m} (x(i+(k-1)\tau) - x(l+(k-1)\tau))^2} \tag{6}$$

Given m and τ, the correlation dimension of the strange attractor can be expressed as:

$$D_2(r,m) = \lim_{r\to 0} \frac{\ln C(r,m)}{\ln r} \tag{7}$$

where C(r, m) is the probability of $r(i, l)<r$, i.e., the accumulating distance distribution function and is given by:

$$C(r,m) = \frac{2}{N(N-1)} \sum_{i=1}^{N} \sum_{l=i+1}^{N} \theta(r - r(i,l)) \tag{8}$$

where, $\theta(\cdot)$ = The Heaviside function and is given by:

Table 2: Mean of rolling bearing friction torque in physical space

	Sequence number of rolling bearing					
Item	1	2	3	4	5	6
Mean of rolling bearing friction torque, X_m/mA	0.3865	0.3760	0.3960	0.3452	0.3502	0.3651

Table 3: Parameter of phase trajectory of rolling bearing friction torque in phase space

	Sequence number of rolling bearing					
Item	1	2	3	4	5	6
Average period, P	32	32	32	30	30	30
Delay time, τ	5	6	6	2	3	2
Embedding dimension, m	7	6	7	5	11	4
Maximum Lyapunov exponent, λ_1	0.1668	0.0638	0.1024	0.1362	0.0914	0.1221
Predictable time, T_m/(24h)	5.995	15.674	9.766	7.342	10.941	8.190

Table 4: Parameter of chaotic evolution of rolling bearing friction torque in phase space

	Sequence number of rolling bearing					
Item	1	2	3	4	5	6
Saturated embedding dimension, m_0	12	14	16	16	16	14
Estimated correlation dimension, D_2	3.3371	3.3384	3.3434	2.8650	3.9207	3.5503

$$\theta(r-r(i,l))=\begin{cases}1; r\geq r(i,l)\\0; r<r(i,l)\end{cases} \tag{9}$$

In practical calculation, the limit $r\rightarrow 0$ cannot be satisfied, then a graph about ln$r$-ln$C$ (r, m) is plotted commonly in order to obtain an estimated value D_2 of the correlation dimension D_2 (r, m). When $m\geq m_0$ where m_0 is called the saturated embedding dimension, the curves in this graph are approaching parallel each other and denser distributing. At this time, the slope of the curve in its linear range corresponding to $m = m_0$ is just the estimated correlation dimension D_2. The value of D_2 no longer changes with the increase of m.

RESULTS AND ANALYSIS

For the time series of the rolling bearing friction torque studied in the experiment, the results in physical space and in phase space are presented in Table 2 and 3, respectively. Given the delay time τ and the embedding dimension m in accordance with Table 3, the diagramed results of the phase trajectories of the six rolling bearing friction torques are shown in Fig. 7 to 12.

It can be seen from Table 3 that the maximum Lyapunov exponent λ_1 is greater than zero, the time series of the rolling bearing friction torque studied in the experiment can therefore be considered as the chaotic time series, i.e., the rolling bearing friction torque is characterized by nonlinear dynamics. In addition, the predictable time T_m takes values in range from 5.995 to 15.674 days, revealing that the friction torque can be predicted when the rolling bearing runs in changing vacuum.

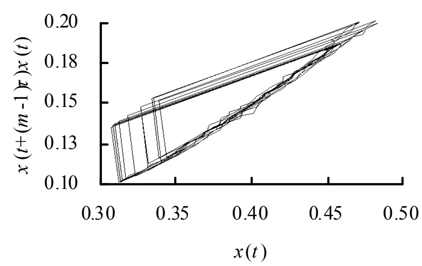

Fig. 7: Strange attractor of friction torque of rolling bearing 1

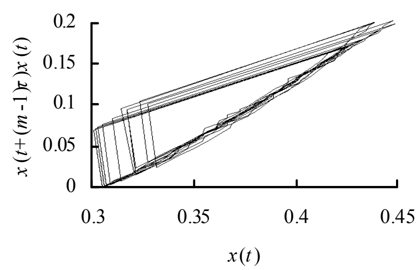

Fig. 8: Strange attractor of friction torque of rolling bearing 2

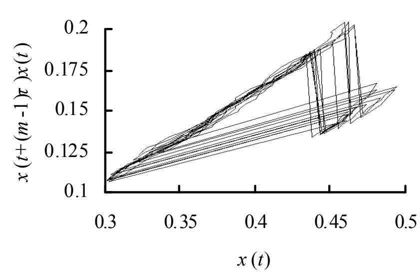

Fig. 9: Strange attractor of friction torque of rolling bearing 3

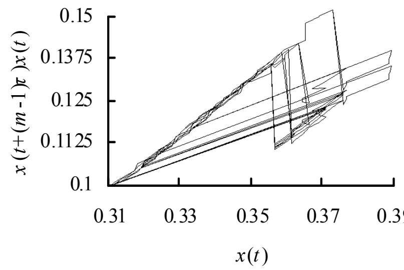

Fig. 10: Strange attractor of friction torque of rolling bearing 4

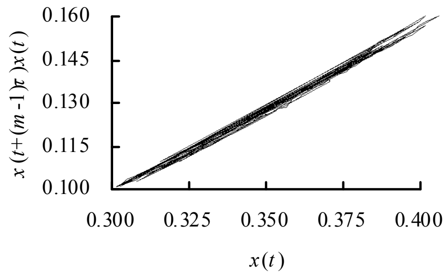

Fig. 11: Strange attractor of friction torque of rolling bearing 5

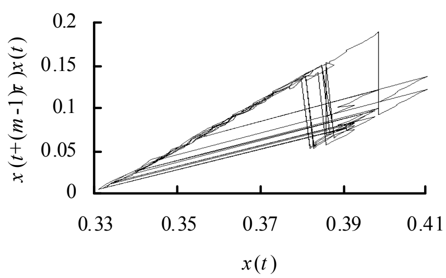

Fig. 12: Strange attractor of friction torque of rolling bearing 6

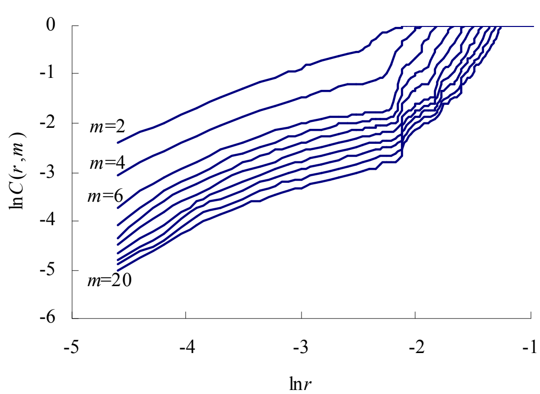

Fig. 13: Graph of ln$r$-ln$C$ (r, m) of friction torque of rolling bearing 1

It is very easy to see from Fig. 7 to 12 that different rolling bearings display different strange attractors.

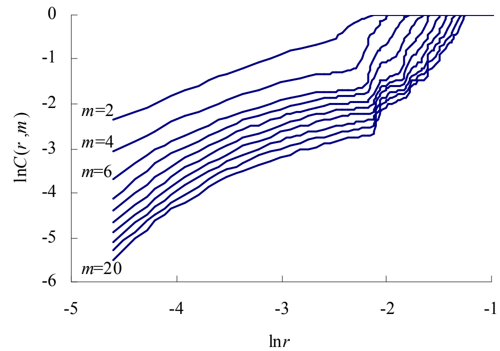

Fig. 14: Graph of ln$r$-ln$C$ (r, m) of friction torque of rolling bearing 2

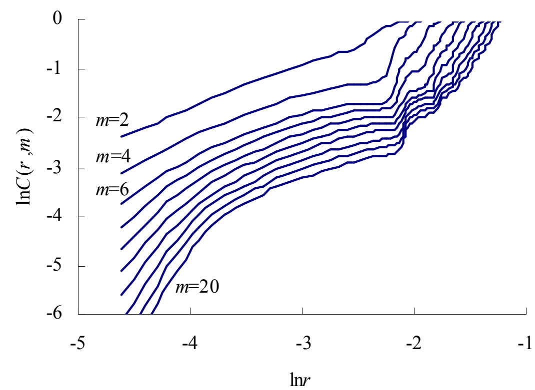

Fig. 15: Graph of ln$r$-ln$C$ (r, m) of friction torque of rolling bearing 3

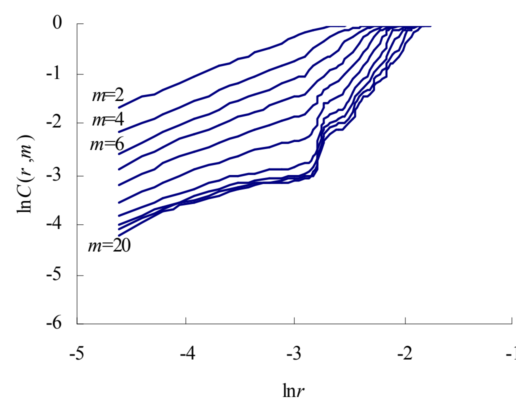

Fig. 16: Graph of ln$r$-ln$C$(r, m) of friction torque of rolling bearing 4

This indicates that the rolling bearing friction torques show a variety and complexity in phase space although they have same rules, viz., the regularly linear increase in physical space, as shown in Fig. 1 to 6. This variety and complexity, in fact, is one of the chaotic behaviors. In order to uncover the nature of the variety and complexity, the estimated correlation dimension D_2 of the rolling bearing friction torque are discussed below.

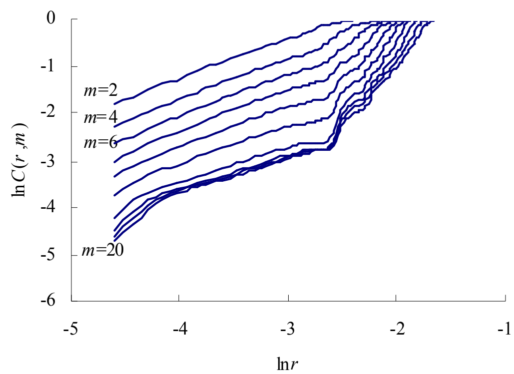

Fig. 17: Graph of ln$r$-ln$C$(r, m) of friction torque of rolling bearing 5

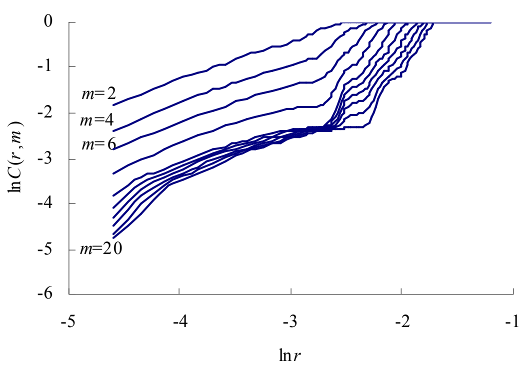

Fig. 18: Graph of ln$r$-ln$C$(r, m) of friction torque of rolling bearing 6

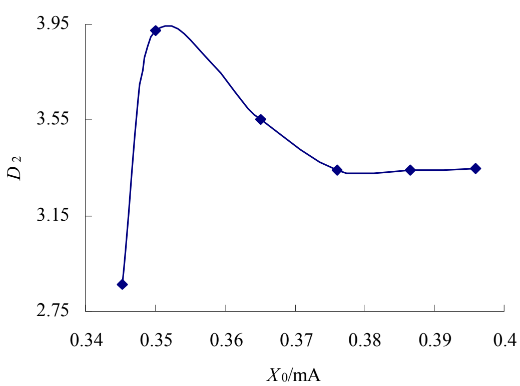

Fig. 19: Relation of estimated correlation dimension with mean of rolling bearing friction torque

In calculating the correlation dimension the delay τ is given in the light of Table 3. The ln$r$-ln$C$ (r, m) graph about the time series in Fig. 1 to 6 is shown in Fig. 13 to 18. The saturated embedding dimension m_0 and the estimated correlation dimension D_2 are listed in Table 4.

From Table 2 and 4, the relation of the estimated correlation dimension D_2 in phase space with the mean X_0 in physical space is obtained, as shown in Fig. 19. Clearly, the estimated correlation dimension D_2 presents a nonlinear and non-monotonic trend with the increasing mean X_0. As a result, the mapping from physical space to phase space is nonlinear and non-monotonic. This is the intrinsic operative mechanism of nonlinear dynamics of the friction torque of the rolling bearing that runs in changing vacuum.

CONCLUSION

In physical space, the rolling bearing friction torque increases with the decreasing vacuum, but, in phase space, different rolling bearings display different strange attractors and show variety and complexity forms with the decreasing vacuum.

The friction torque is of the chaotic time series because its maximum Lyapunov exponent is greater than zero and it can therefore be predicted when the rolling bearing runs in changing vacuum.

The intrinsic operative mechanism of nonlinear dynamics of the friction torque of the rolling bearing is characterized by a nonlinear and non-monotonic trend of the estimated correlation dimension with the increasing mean of the friction torque,.

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