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Early fault detection of rotating machinery through chaotic vibration feature extraction of experimental data sets

A. Soleimani, S.E. Khadem*

Faculty of Mechanical Engineering, Tarbiat Modares University, P.O. Box 14115-177, Tehran, Iran

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ABSTRACT

Fault detection of rotating machinery by the complex and non-stationary vibration signals with noise is very difficult, especially at the early stages. Also, many failure mechanisms and various adverse operating conditions in rotating machinery involve significant nonlinear dynamical properties. As a novel method, phase space reconstruction is used to study the effect of faults on the chaotic behavior, for the first time. Strange attractors in reconstructed phase space proof the existence of chaotic behavior. To quantify the chaotic vibration for fault diagnosis, a set of new features are extracted. These features include the largest Lyapunov exponent; approximate entropy and correlation dimension which acquire more fault characteristic information. The variations of these features for different healthy/faulty conditions are very good for fault diagnosis and identification. For the first time, a new chaotic feature space is introduced for fault detection, which is made from chaotic behavior features. In this space, different conditions of rotating machinery are separated very well. To obtain more generalized results, the features are introduced into a neural network to identify different faults in rotating machinery. The effectiveness of the new features based on chaotic vibrations is demonstrated by the experimental data sets. The proposed approach can reliably recognize different fault types and have more accurate results. Also, the performance of the new procedure is robust to the variation of load values and shows good generalization capability for various load values.

1. Introduction

Most of the rotating machinery used in the industry operates by means of bearings and gearboxes. Machinery faults can occur for many different reasons including imperfect design, incorrect installation, corrosion, erosion, poor lubrication and plastic deformations. Ball bearings and gearboxes are the main causes of failure in rotating machinery. To avoid downtime and increase reliability, early fault detection in rotating machinery has been the interest of many researchers.

Thus, there is a need for non-destructive techniques for fault detection and diagnosis of rotating machineries. The most successful methods are currently based on analysis of vibration signals. Vibration characteristics of the rotating machinery depend on various factors such as shaft rotational speed, clearance, load, stiffness, surface waviness. By using the signal processing techniques, one can obtain important information from the vibration signals for fault diagnosis. Accordingly, several methods based on vibration signal analysis have been developed.

Traditional vibration signal processing techniques can be divided into time, frequency and time–frequency domain methods. These methods are suitable for linear systems which have stationary signals and periodic phenomenon. Early fault detection of rotating machinery with complex and non-stationary vibration signals in presence of noise is very difficult. Therefore, there is a need to develop effective diagnosis methods using novel signal processing procedures for extraction sensitive features of machinery faults and operating conditions.

* Corresponding author. Tel.: +98 2182883388; fax: +98 2182883388.
E-mail address: khadem@modares.ac.ir (S.E. Khadem).

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In linear systems, the response to harmonic excitation forces only contains the frequencies of the harmonic excitation forces. But, in the nonlinear systems, the response to harmonic forces may have many possibilities, including sub-harmonics and super-harmonics, quasi-periodic and chaotic motions. The necessary and insufficient requirement for having chaotic behavior in dynamical systems is to have nonlinearity in the system.

On the other hand, many faults and various operating conditions in rotating machinery involve significant nonlinear dynamical properties. So, new vibration signal analysis techniques based on chaos theory and nonlinear dynamics are very useful. Also, the use of chaos analysis tools in machine vibration signal analysis is still a novel method, but the chaos analysis tools have been used extensively in other fields such as medical engineering for heart signal analyzing. So far, a few papers in the literature have discussed the effect of machine faults on the chaotic vibration features.

The vibration of rolling bearing with varying clearances was considered in [1]. Constant stiffness of rollers was used to modeling the vibration of roller bearings. In the study of periodic vibration caused by the clearance variations at the low speeds, a non-periodic vibration at higher speeds was revealed. In the simulation of a rotor bearing system with waviness, the quasi-periodic and sub-harmonic vibration was observed [2].

The correlation integral was used for detecting the bearing faults [3,4]. The dimension of the vibration signals was determined by using the correlation integral. The experimental results showed a reduction in the dimension of the system caused by the outer race fault in bearing.

A new fault diagnosis method with the wavelet packets, fractal dimension and a neural network was used for rotating machinery [5]. This study considered different faults including imbalance, misalignment, looseness, and imbalance combined with misalignment. The wavelet packets transform is applied to the measured vibration signals, and then, the box-counting dimension of each frequency bands is extracted to identify fault characteristics. The different faults are classified by a radial basis function neural network. The experimental results show that the proposed method can effectively detect and recognize different kinds of faults of rotating machinery.

The Poincare map was modified for damage detection in tapered and roller bearings [6]. The cage speed was used for Poincare map which has good information on the fault type.

By the numerical simulations of a nonlinear model for bearings, a sub-harmonic route to chaos was observed [7]. In the competition between the ball pass frequency and the first natural frequency, a sub-harmonic vibration was revealed. When the ball passage frequency was near the second natural frequency of the rotor system, a quasi-periodic route to chaos was identified.

By using an experimental test bench, a numerical method was used to construct Poincare section [8]. Bearing clearance was varied as the control parameter and the presence of instability was observed in its vibration. Two different routes to chaos in the vibration of ball bearing have been identified through experimental data. About the horizontal resonance frequency, the system is unstable and generates some sub-harmonics of the excitation frequency at the ball passage frequency. Around the vertical resonance frequency, also, a sub-harmonic motion is observed which was the first route-to-chaos associated with the first resonance frequency. When the speed reaches the second critical speed, a quasi-periodic motion is identified which is the second route associated with the second resonance frequency.

It is found that the bearing vibration signals demonstrated complicated nonlinear characteristics [9]. The application of the multi-scale fractal dimensions (MFDs) based on morphological cover techniques was used for bearing fault diagnosis. The MFDs can provide discrimination about the vibration signals of different faults. This method was verified by experimental test results which show that the MFDs were a suitable method to improve the performance of bearing fault diagnosis.

The dimension of the vibration signal is used to crack detection in a gearbox [10]. Also, the dimension value for different crack size and several shaft speeds was considered. The results show that the dimension of gearbox signal is a global feature which has more information about the gear dynamics.

In civil engineering, the fractal analysis is used for damage detection in concrete structural elements. The results show that the fractal dimension of the damaged structure is decreased from an initial value [11].

When a dynamical system has no damping, the chaotic motion that can occur is known as Hamiltonian chaos and when there is a damping, dissipative chaos can occur. Since real systems always have energy dissipation mechanisms, then, the dissipative chaos is more useful to study chaotic behavior in rotating machinery. Dissipative chaos is analyzed by employing various established features such as Lyapunov exponent, fractal dimensions and approximate entropy.

The focus of the current paper is to study the effect of different faults on the chaotic vibration of the system. To study the effect of faults on the chaotic vibration, the phase space is reconstructed, here, for the first time. The reconstruction of the phase space for different healthy/faulty conditions is a new method to study nonlinear effects of faults on the chaotic vibration. Obtained phase spaces show strange attractors which prove the existence of chaotic vibration. Also, the strange attractors are different for healthy/faulty conditions and hence have different characteristics. To quantify the characteristics of strange attractors, a set of new features are extracted from the reconstructed phase space. These features include the largest Lyapunov exponent; approximate entropy and correlation dimension which acquire more fault characteristic information. The variation of these features for different healthy/faulty conditions is very good for fault diagnosis and identification. These features are used to construct a new space named chaotic feature space, here, for the first time. Different healthy/faulty conditions are well separated in the chaotic feature space. To obtain more generalized results, the features are introduced into a neural network to achieve an intelligent fault detection system. One of the most significant issues in intelligent monitoring is related to feature extraction. This paper mainly focuses on finding proper features based on chaotic vibration for machine fault detection and classification.