Health Monitoring and Vibratory Fault Prediction of Rotating Machinery

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ABSTRACT

The major rotating machines such as large centrifugal or axial flow compressor, gas turbine and aero-engine are in the value chains of high-end and the core aspects of the industry factories, regarded as important embodiments of the national core competence in industry and high-technology development. The health monitoring and fault diagnosis and prediction, belonging to the technologies of prognosis and health management (PHM) are widely focused in recent years and developing constantly. The principles of health monitoring and vibratory fault prediction of rotating machinery are introduced in this paper. The dynamics of rotor system and structures are introduced, and the vibration problems of the rotating machine or structures are interpreted. The diagnosis and prediction of vibration faults happening on these machines commonly are given with examples of bearing faults of a turbine test-rig. At last, some important research tasks in future are prompted.

1. INTRODUCTION

Rotary machinery, i.e. large centrifugal or axial flow compressor, steam turbine, gas turbine, aero engine, etc., is at the core of the value and industry chain, is an important embodiment of the core competence and technical level of the national industry. For example, the large centrifugal compressors are widely are used in the field of natural gas, petroleum and coal chemical industry, shown as Fig. 1 which is the large compressor set used in a million-ton level ethylene plant, made by Shenyang blower (Group) Co. Ltd, China in 2015.

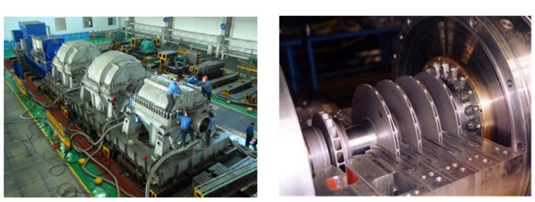


Fig. 1 A large compressor set and its rotating discs and shaft

Another important engineering product is the aero-engine, which is well known as the typical high-tech one related to national military security and national economic development. Until now China does not have the ability to design and manufacture the commercial high-bypass aviation engine. The developing high-bypass turbofan engine of CJ1000 can service until 5 years later, which is made in Shanghai of China. But there is a large gap from Chinese domestic products to the international ones in terms of work efficiency, stability, safety and reliability.

With the development of modern technology, rotating machinery is going towards large-scale, continuous, high speed, concentration, automation and high power, heavy load, which also makes rotating machinery failure probability increases greatly. These machines in industrial plant as key equipment are very expensive cost a few million dollars, and a single day's loss of shutdown may be very huge. Maintenance is of high importance but very difficult even many researchers and companies have made a lot of efforts and contributions. Over the years, companies have learnt to minimize the downtime of a given rotating machine so that the best returns can be obtained. Obviously the smart maintenance is an important factor to make the downtime to minimum.

However, there is no comprehensive and effective technology to completely solve the problem until now. Recently, the maintenance programs for rotating machinery are developing into preventive maintenance and predictive maintenance [1, 2]. In order to truly implement the preventive or predictive maintenance in practice, several advanced but practical technologies, mostly associated with health monitoring and fault prediction, are prompted to be broken down. On the other hand, the various indicators used to study the health of the machine, especially to deal with vibratory faults often occurred on the machine, are predominantly vibratory related; after all, any change in the condition of the machine affects its dynamic conditions and therefore the vibratory behaviors.

The health monitoring and fault prediction of rotating machinery include the following 6 aspects: 1) health monitoring strategy and fault prediction principles; 2) fault mechanisms of rotor systems and structures; 3) advanced measurement technologies; 4) advanced signal data processing technologies; 5) vibration fault detection and diagnosis; 6) fault prediction and life estimation.

Some successful examples and cases are introduced. The most important contribution is to identify what is truly effective for practical plant maintenance among these proposed technologies.

2. PRINCIPLES OF HEALTH MONITORING AND FAULT PREDICTION

Vibration faults of rotating machines are popular and very serious in many countries. The aero-engine fault statistics of China are: 1) the performance fault is about 10~20% of the total fault, and 2) the structural strength failure accounts for 60~70%.

The technology of prognostics and health management (PHM) is the core of advanced maintenance of machinery. As we know, the maintenance programs with PHM for machinery can be broadly classified into three categories, viz., 1) run to failure; 2) preventive maintenance; 3) predictive maintenance. The best method of maintenance or the last one is to predict a brewing problem in a machine and attend to the problem if possible while it is being run, namely predictive maintenance.

The development of PHM technology has experienced three stages: 1) fault diagnosis; 2) fault prediction; and 3) integrated implement PHM system.

The health state is different from the abnormal state, fault state and the failure state, which is the ability of coping with the circumstances and fulfill the prescribe task. Health state is rated as the following three sub-states: 1) Health: the equipment operation being stable without performance degradation; 2) Sub-health: existing potential failures, but without performance degradation; 3) Danger: with performance degradation, but not failure.

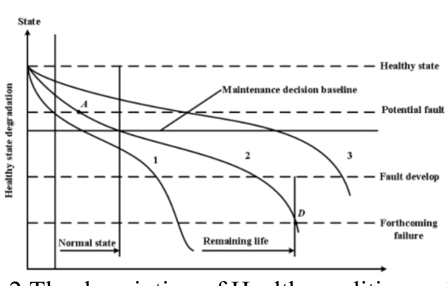


Fig. 2 The description of Health condition and its degradation of machinery

Health state evaluation of equipment is on the basis of condition monitoring. The condition monitoring techniques have changed over years as the machines become more and more sophisticated, with increasing capacities and speeds and the availability of more accurate instrumentation and faster computers. The change in maintenance patterns is three steps, i.e. 1) run-to-breakdown; 2) time-based preventive; 3) condition-based maintenance. In particular, the latter two are important details of the new condition monitoring, troubleshooting and health management. The significant changes do not go directly towards the fault elimination, but the forecast fault development trend.

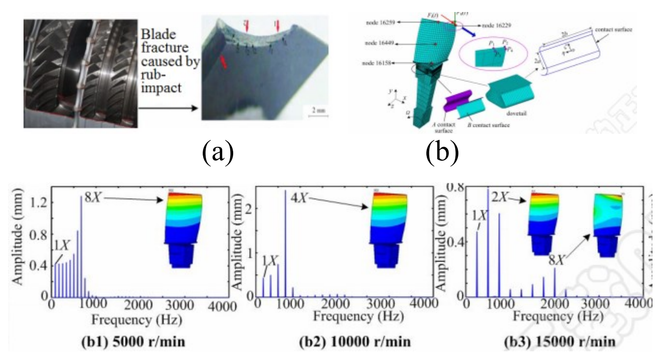
The health condition and its degradation of a machinery is illustrated as Fig. 2 [2].

3. FAULT MECHANISMS OF ROTOR SYSTEMS AND STRUCTURES

In order to achieve health monitoring and assessment, fault diagnosis and fault/lifespan prediction, dynamics analysis and fault principles of machinery are fundamentally required, especially facing different vibration faults. They are rotor system and assembly, typical characteristics of a rotor system with faults, excessive coupling vibration and the fatigue damage of structures, excessive fluent-solid coupled vibration and the fatigue damage of structures, and so on.

Take unsteady rotor vibrations caused by the rub-impact as example. Due to increasing demands for high speeds and high efficiencies, the clearance between rotors and stators in modern rotating machineries has become smaller and smaller. A typical case can be observed in aircraft engines where the clearance between the engine blade tips and engine casing being often designed to be as small as possible in order to increase efficiency. As a result, the rub-impact, which refers to the contact between rotating and non-rotating structures in a machine, has become a common malfunctions of rotating machineries. Rub-impact induced vibration faults can cause: 1) Serious vibration of whole engine, and 2) Vibration fatigue of blade and/or sealing.

In the case of rub-impact, the rotor system suffers great vibrations showing as multi-harmonic responses. Also, the rub-impact induced high-modal resonances of blade are useful to monitoring the state of blade and detecting possible fault happening on blade, as shown in Fig. 3 [3, 4].



(c)

Fig. 3 the rub-impact induced high-modal vibrations of a blade

4. ADVANCED SIGNAL DATA PROCESSING TECHNOLOGIES

The vibration signal in time domain is useful to the extent of finding out the overall vibration level. Guidelines for determining acceptable levels of different types of machinery have been standardized over years.

In complex machinery such as turbines with several stages and coupled rotors, there could be several frequencies that are responsible in deteriorating the condition of the machine, e.g., unbalance, misalignment, bearing looseness etc.

Normally, the frequency domain analysis that is responsible for a particular defect is to be identified rather than the overall vibratory level.

Moreover, most of the vibration signals measured from a machine, are mainly regarded that there are: 1) contaminated noises, 2) stationary and/or non-stationary properties, and 3) linear and/or nonlinear properties.

The common used data processing techniques in time domain, frequency domain and time-frequency domain are listed in Tab. 1 for condition monitoring and fault prediction of rotating machinery.

Tab. 1 Common used data processing techniques for rotating machinery

Time-domain analysis	**Frequency-domain analysis**	**Time-frequency analysis**
1 P to P value 2 RMS 3 Kurtosis 4 Mean value 5 Variance 6Standard deviation 7 Form factor 8 Peak factor 9 Impulse Factor 10 Margin factor	Fx, (Rotating frequencies) 1/2Fx 2Fx 3Fx …… Fi Fo Fc Fn	Wavelet Wavelet package ARMA Karlman Filter HMM HTT Spectrum envelope

Take kurtosis value changes due to bearing damage as example. A rotor test-rig supported by two bearings shown in Fig. 4.The vibration signals measured on the bearings' house are compared for both the normal and the cage damage. The multi-harmonic frequency components appear in spectra, but it is not clear to indicate the possible damage in bearing; the calculated Kurtosis values of the measured bearing vibrations show that they change from 3 to 5 which indicate there are damage happening in the bearing, shown in Fig. 5.

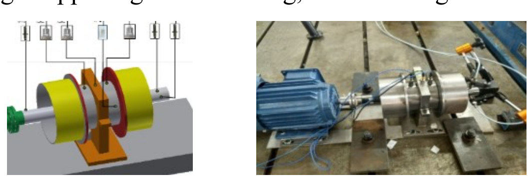
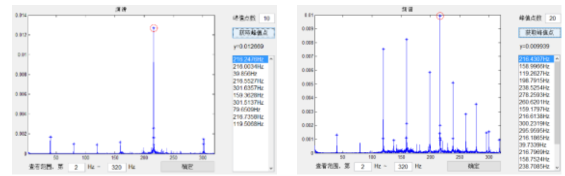
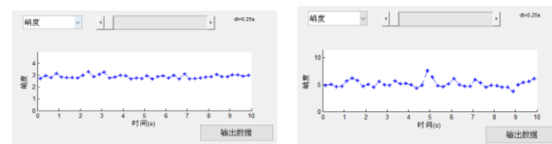


Fig. 4 A rotor test-rig supported by two bearings



(a) normal bearing (b) damaged bearing



(c) normal bearing (d) damaged bearing

Fig. 5 Vibrations and spectra and Kurtosis value measured on a bearing house

5. VIBRATION FAULT DETECTION AND DIAGNOSIS

The technologies of fault diagnosis has developed for over 40 years. The gain of fault diagnosis is often to confirm: 1) fault pattern, 2) fault cause, 3) fault location, 4) fault level, and 5) fault happening time, and so on.

The fault diagnostic procedures are: 1) data extraction, 2) preprocessing, 3) feature extraction of fault, 4) classification and identification, 5) decision-making, and 6) maintenance management.

The commonly used fault diagnostic methods are: 1) Expert system, 2) Logical reasoning, 3) Statistical pattern recognition, 4) Fault tree analysis, 5) Neural network, 6) Support vector machine, 7) Fuzzy Logic. Whether data-driven based, analytical or knowledge-based methods, each of these presents advantages and disadvantages. Therefore, there is no one method is best to all the applications. The best process monitoring or fault diagnosis scheme is considering multiple technology, the fault detection, identification and diagnosis are conducted by kinds of statistical characteristic parameters methods.

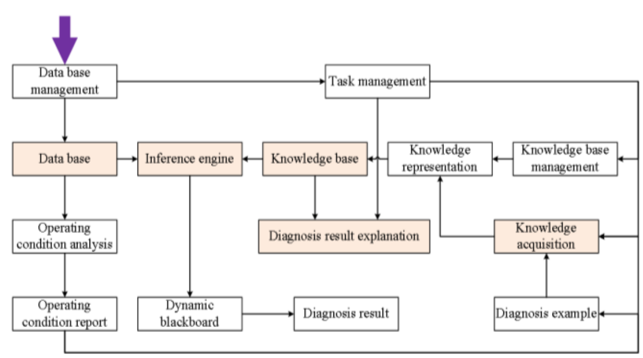


Fig. 6 Framework of an ES based fault diagnosis for bearing faults

The mostly happening vibration fault patterns in rotating machinery are: 1) Unbalance of rotor, 2) Rub-impact, 3)

Misalignment of shaft or supporting, 4) Damages of bearing or supporting, 5) Cracks on disc and blade and shaft, 6) Fluid-induced resonance, 7) Thermal bending shaft, etc.

The Knowledge-based system is to solve practical problem through the knowledge and inference methods of mankind experts. An ES frame is composed of: 1) Knowledge base, 2) Inference engine, 3) Signal data base, 4) Interpretive routine, 5) Knowledge acquisition. The framework of an ES based fault diagnosis for bearing faults is shown Fig. 6. The interface of the software of it is as Fig. 7.

Fig. 7 Interface of an ES based fault diagnosis for bearing faults

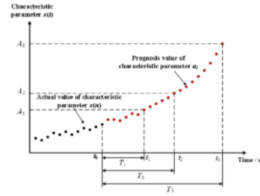
6. FAULT PREDICTION AND PREDICTIVE MAINTENANCE

Depending on the machine components and experience of prior failures, one can predict the lifetime from overhauls or planned shutdowns to carrying out repairs. Maintenance is carried out on a planned scale, some parts are replaced, e.g., the blades of a turbine as their expected life is completed. Such a maintenance process prevents possible failures and keeps the downtime to a minimum. The best method of maintenance is to predict a brewing problem in a machine and attend to the problem if possible while it is being run. Obviously there has to be several indicators that reflect on the condition of the machine.

A lot of instrumentation, recording equipment and analysis is required before a decision can be made on the condition of the machine so that any fault can be corrected or that the machine can be shut down before a failure.

Also, the fault prognosis can also be achieved based on ARMA model. Take bearing fault prognosis based on ARMA model as example, the determination of thresholds and the timespan are shown in Fig. 8, and the practical data together with the predicted data are compared in Fig. 9.

The abnormal condition determination threshold A1=0.04, fault condition determination threshold A2=0.06, failure condition determination threshold A3=0.08 are also set empirically. The three timespans that the bearing costs for reaching three states are obtained.



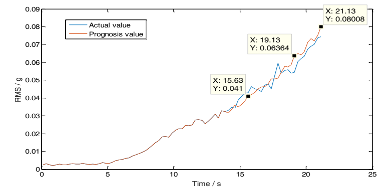


Fig. 8 thresholds and timespan definition Fig. 9 Bearing cage crack fault prognosis based on ARMA model (p=5, q=8)

7. CONCLUSIONS AND PERSPECTIVE STUDIES

The health monitoring and fault prediction system for rotating machineries are important for both research and industries. As typically seen in aircraft engines, since failures in such machines may cause serious accidents, it is strongly focused.

The urgent needs of fault prediction maintenance come from industry, both manufacturers, and processing or repairing companies. The dynamics of system or structure with fault are important for maintenance technology. Model based fault detection and prediction are developing now. The lifetime estimation is not only based on fatigue but also the fault theory. New machines are developing and so as the new challenges for predictive maintenance

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