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. Some new developed sensor technologies are also described to show their efforts on direct measurement and condition monitoring on the machine. 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.

Keywords: Health monitoring, Vibratory fault diagnosis, fault prediction, rotating machinery

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

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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.

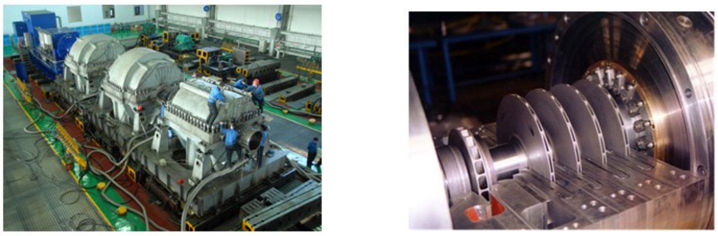

Fig. 1. A large compressor set and its rotating discs and shaft

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, shown in Fig. 2. But there is a large gap from Chinese domestic products to the international ones in terms of work efficiency, stability, safety and reliability.

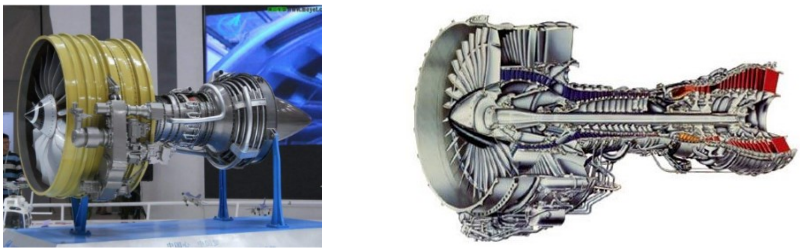

Fig. 2. High by-pass turban engine and its rotor system

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.

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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.

Taking the aero-engine rotor system and its blades as examples, several vibratory faults are presented to reveal new mechanism and give new vibration behaviors, such as blade rubbing-impact, rotor cavity oil induced instability, elastic-supporting misalignment and high order resonance induced fatigue of blade. Optical fiber-Bragg sensors and wireless strain transducers are introduced into the measurements of bearing deformations or blade cracks. The obtained vibration signals of machine and structure are processed to extract the feature parameters to indicate sensitively the healthy or fault conditions by using of time and/or frequency domain analyses. The fault diagnoses are classified as data driven and model based, either statistical or artificial intelligent ones. At last, the main difficulty of fault prediction lies in the evolution process of a fault and the happening time of failure, and the estimation of fault remaining life length. Both evolution speed based and state model based prediction technologies are investigated by using an example of bearing damage fault.

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 Vibration fault description

Why do rotating machines deteriorate in their performance and fail? The reasons are: 1) The moving parts all rub against other moving parts or stationary surfaces; 2) Continuous wear takes place, clearances change and machine behavior from the designed condition changes; 3) Bolts and other fasteners may get gradually loosened; 4) The moving parts may be subjected to increased unbalance due to corrosion, erosion; flow medium particle impact etc.; 5) The alignment between the driver and driven machines gets affected due to continuous vibrations that exist in a machine; 6) The seals get rubbed and lose their effectiveness over a period of time [3].

The typical faults and damages of rotating machinery structures are shown as Fig. 3, where many faults and damages are induced unexpected vibrations.

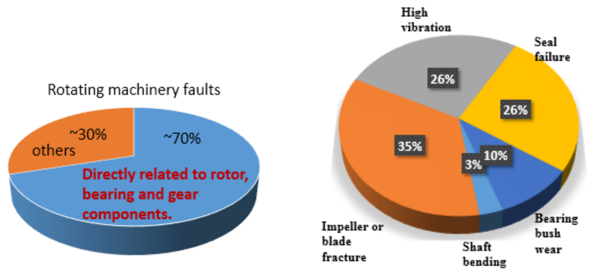

Fig. 3. Typical faults and damages of rotating machinery structures

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%.

There are two categories of Vibration faults: 1) System vibration problem, i.e. excessive vibration, vibration sensitivity, vibration instability, etc.; and 2) Structure vibration problem, i.e. high cycle fatigue (HCF), happening on most of the structural strength failure. The faults of the disc, blade, shaft, bearing and other structural parts are mostly related to the structural vibrations.

***Example* 1: Vibrations of a jet engine**

A jet engine runs from 33% to 100.2% of the rotating speed, the vibrations of engine have many sub-harmonics, combined harmonics and supper harmonics of the LP and HP speeds, N1 and N2.

(1) The vibrations are stronger than normal;

(2) When a running speed is constant, the vibration amplitudes may change or even increase;

(3) The vibration components coming from HP are larger than those of LP.

It is known that the rub-impact on HP turbine is serious, not on the LP. It is also

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confirmed by dis-assembly checking and found the 5th sealing teeth washing. The measured frequency spectra are shown in Fig. 4.

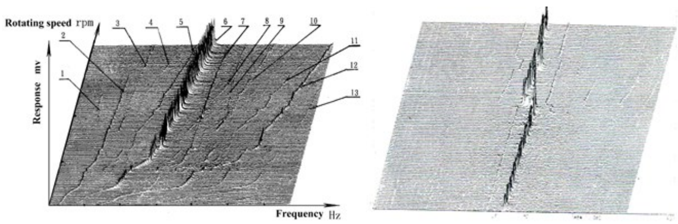

Fig. 4. The measured frequency spectra of vibrations of turbojet engine

***Example* 2：Vibration induced damages of blades**

Serious accidents caused by the vibration fatigue of blades, discs, and bearings and so on. The direct reason of above is vibration fatigues. The underlying reason is mainly the structural vibration caused by complex sources (sound, gas and solid coupling modes, etc.). Figure 5 shows the typical fatigue of discs due to higher order and lower order vibrations respectively.

Fig. 5. damages of structure and disc fatigues due to vibration

Therefore, strong demands for collaborative innovation in rotating machinery, including: 1) materials, i.e. titanium alloy, high temperature alloy, composite material, and so on; 2) design, considering carefully complex flow and aerodynamics, structural strength and vibration; 3) manufacturing, involving advanced manufacturing, remanufacturing etc.; 4) advanced maintenance technology.

3 Principles of health monitoring and fault prediction

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.

It has a long period of development in the PHM fields of industrial equipment to achieve in two levels: 1) parts level; and 2) systems level. The essential steps are: 1) state recognition; and 2) state classification, which are to identify the running status of the equipment based on run-time information.

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

3.1 Framework of Health monitoring and fault prediction

An example of a PHM system developed for aircraft is given to show the requirement and framework of health monitoring and fault prediction, shown as Fig. 6 and 7 respectively [2].

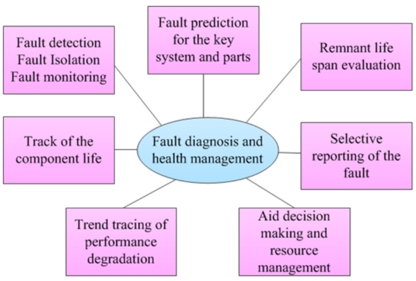

Fig. 6. Requirement of fault diagnosis and health management in aerospace

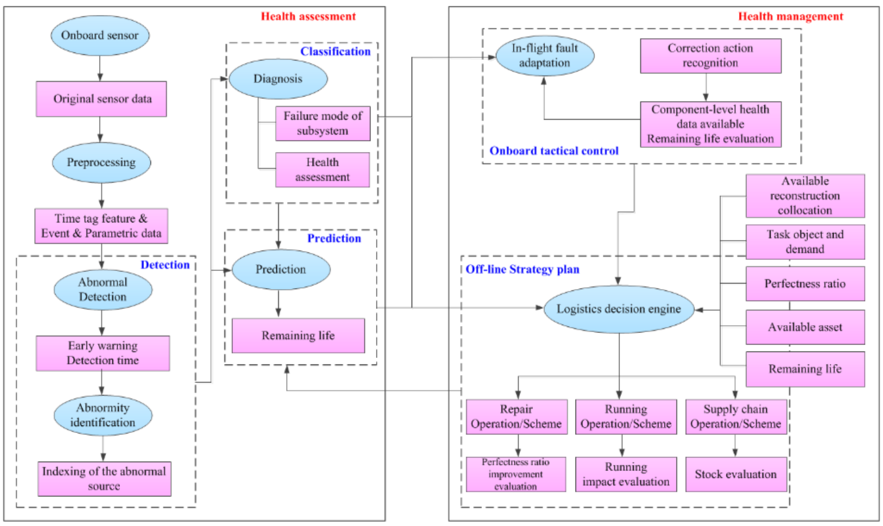

Fig. 7. Framework of PHM proposed for GE aero-engine

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3.2 Basic concept of health condition

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.

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. 8 [2].

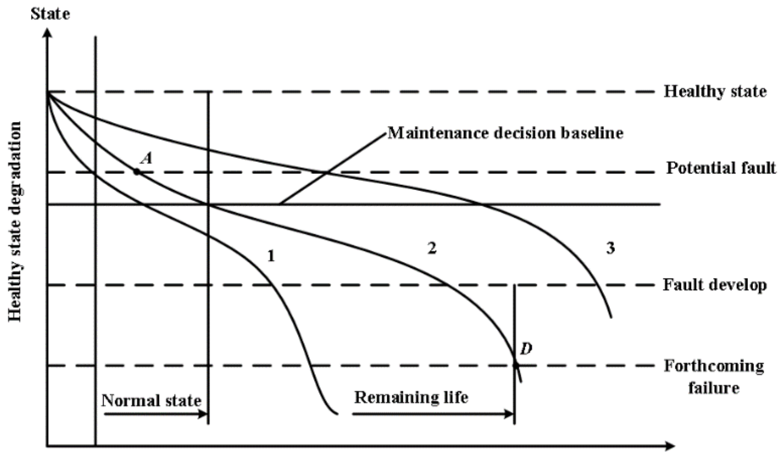

Fig. 8. The description of Health condition and its degradation of machinery

3.3 Health evaluation and fault prognosis

After each feature extraction, adaptive clustering is used to perform health assessment of the machine in real-time. The principle of health evaluation is shown as Fig. 9, including two categories of model based one and data driven one.

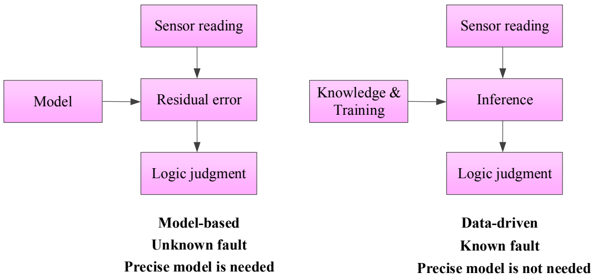

Fig. 9. Health evaluation methods

Fault prognosis is to predict the result of the components or the system fulfilling its function, performance degradation or the approach of the failure, including to confirm the residual life and the normal working times. The fault trend and prediction of a gear (as an example) is described as Fig. 10 [2].

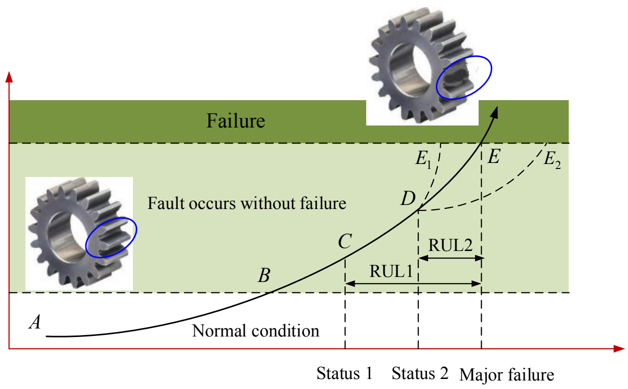

Fig. 10. Fault trend and prediction

The fault prognosis can help people to predict the lifespan or remained lifespan of a machine or its part. The idea is shown as Fig. 11 [2].

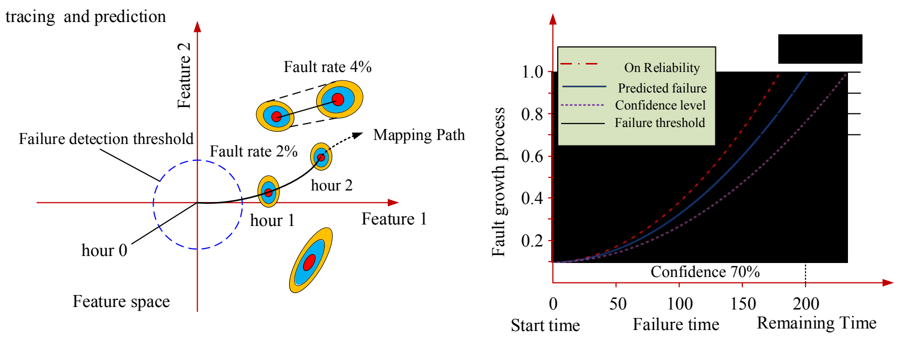

Fig. 11. Fault prognosis and lifespan prediction

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3.4 Methods for condition monitoring and fault diagnostics

The large rotating machinery suffers from operating condition deterioration and faults commonly. The popular faults happening in rotating machines are diverse but often classified into four categories, as shown in Fig. 12.

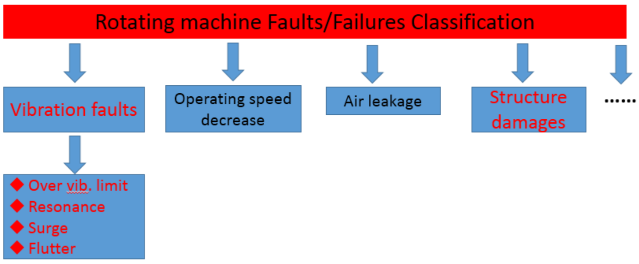


Fig. 12. Popular faults happening in rotating machines

Mostly, it is of importance that vibration information of machine used for health monitoring, fault diagnosis and fault prediction. People have tried various indicators to study the health of the machine, but they are predominantly vibratory related. Any change in the condition of the machine affects its dynamic conditions and therefore the vibratory behavior. Other indicators in use are: sound, wear particles from bearings, temperature of bearings, process parameters such as load, speed, frequency of operation, steam pressure etc.

The popular used methods of condition monitoring and fault diagnosis include the followings:

1) Mathematical models based methods: Based on direct measurements and signal processing, Based on the method of state estimation, Based on the process parameters;

2) Artificial intelligence based methods: Expert system, The database of fault diagnosis cases, etc.;

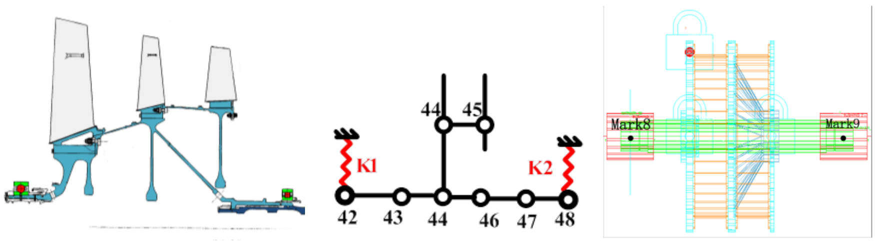
3) Information fusion based methods: Bayesian network, Fuzzy reasoning information fusion, etc..

4 Fault mechanisms of rotor systems and structures

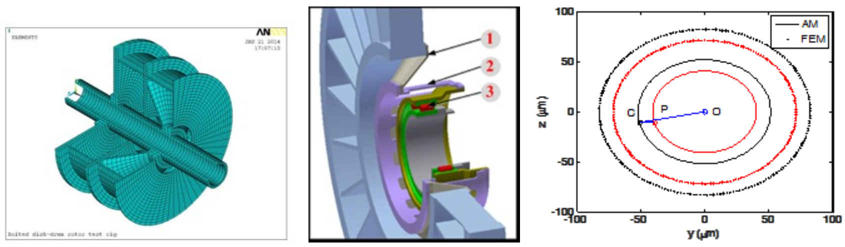
In order to achieve health monitoring and assessment, fault diagnosis and fault/lifespan prediction, dynamics analysis and fault principles of machinery are fundamentally required, especially facing different vibration faults. They are rotor system and assembly, typical characteristics of a rotor system 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.

***Example* 1: Dynamics of fan rotor system and assembly parts**

The fan rotor system of an aero-engine is taken as an example to illustrate the vibration characteristics and behaviors to help the monitoring or fault diagnosis task. The fan rotor system composes of three bladed discs and two bearings fixed in their elastic supporting houses, which is modeled dynamically into different ones including finite element model, multi-rigid-flexible body model, whole 3D finite element model and hybrid models are also useful in many cases for rotor dynamic analysis in the view of multi-level modelling principle, shown as Fig. 13 (a)-(e). The fan rotor system possesses two vibration modes of both translation mode and pitch mode, and behaves unbalanced mass center locating at the opposite direction of the rotating center when running over the first mode, shown as Fig. 13(f).



(a) real structure (b) finite element model (c) multi-body model



(d) 3D finite element model (e) hybrid model of supporting (f) shaft center orbit

Fig. 13. The fan rotor system of an aero-engine models and its shaft center orbit

***Example* 2: Unsteady rotor vibrations caused by the rub-impact**

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

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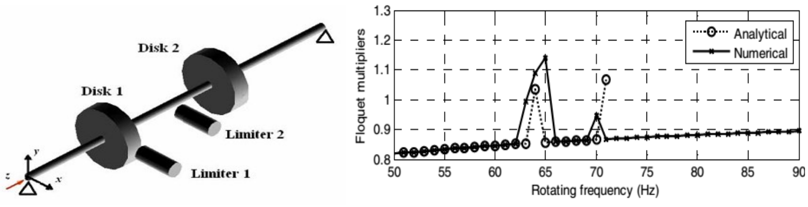
between rotating and non-rotating structures in a machine, has become a common malfunctions of rotating machineries. Rub-impact induced vibration faults can cause: 1) Serious vibration of whole engine, and 2) Vibration fatigue of blade and/or sealing.

Rub-impact induced motion instability of rotor system can be expressed by Floquet stability theory. The Floquet multipliers of a simplified rotor system as demonstrated in Fig. 14(a) are plot as Fig. 14 (b), where the Floquet multipliers greater than 1 implying instability conditions [4].



(a) (b)

Fig. 14. A rotor system happening rub-impact and its Floquet multipliers of motion via rotating speeds

In the case of rub-impact, the rotor system suffers great vibrations showing as multi-harmonic responses. The typical vibration spectra of a rotor system with rub-impact are shown in Fig. 15. These are useful references to detect faults.

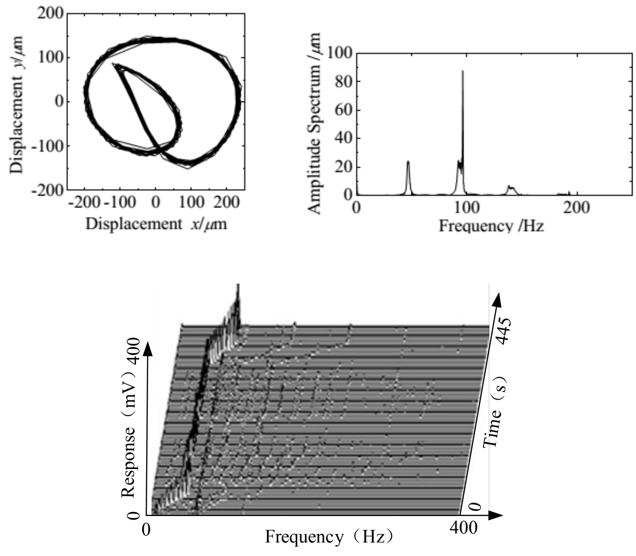


Fig. 15. Typical vibration spectra of a rotor system with rub-impact

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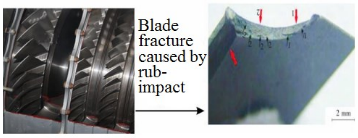
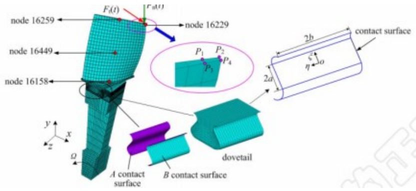
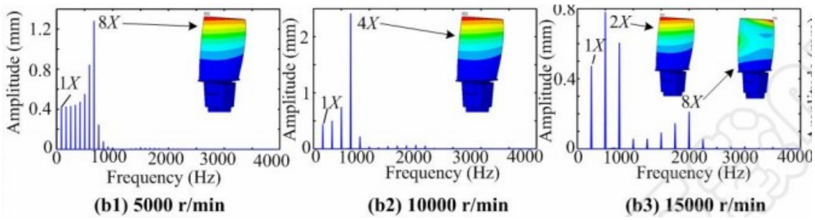
Also, the rub-impact induced high-modal resonances of blade are useful to monitoring the state of blade and detecting possible fault happening on blade, as shown in Fig. 16 [5, 6].



(a)



(b)



(c)

Fig. 16. The rub-impact induced high-modal vibrations of a blade

***Example* 3: Rotor vibrations caused by supporting misalignment**

The long shaft of the low-pressure (LP) rotor system in aero-engine is unavailable to suffer from the supporting misalignment happening on the front or end support. The added stiffness of the misaligned supporting rolling bearing together with its elastic house is determined by the bearing assembly dynamic analysis. The governing equations of the whole LP rotor system with all elastic supports and the misaligned supporting are set up to predict the vibrations of the machine. As shown in Fig. 17, the misaligned supporting and the simplified rotor system are used to simulate the vibrations of the shaft and discs, including the transverse vibrations in three directions [7].

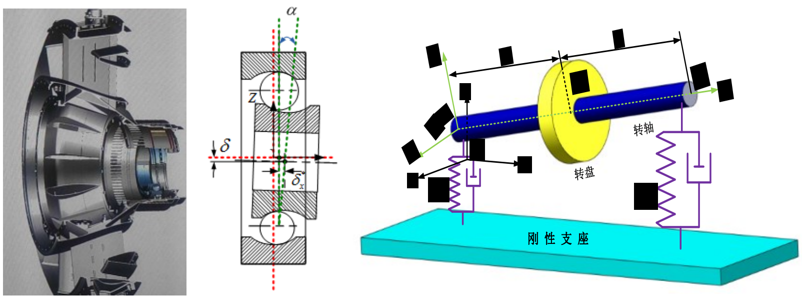


Fig. 17. The misaligned supporting and the simplified rotor system

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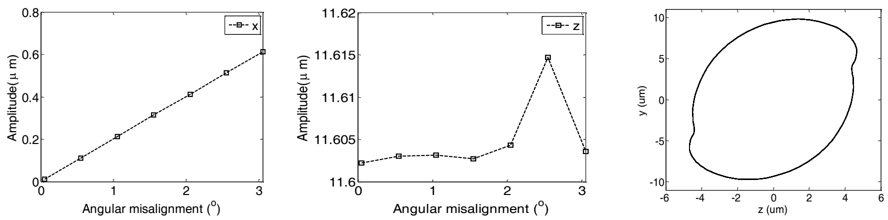
The simulated results shown in Fig. 18 implies that the efforts of the misalignment on the vibrations are as following:

1) With the increasing of the misalignment, the amplitude of the axial vibration increases.

2) When the misalignment angle increases from 0 to 2 degree, the amplitude of the lateral vibration does not change much.



(a) axial disp. –x (b) redial disp. -y (c) shaft center orbit of xy-plane

Fig. 18. The simulated rotor vibrations due to supporting misalignment

5 Advanced measurement technologies

There are many kinds of sensor technologies are used in condition monitoring and fault prediction for rotating machinery, such as thermal, pressure, flux, position, force and motions. The vibration sensing and monitoring are powerful and popular besides above items.

Actually, the current measurement technology is far from the need of health monitoring and fault prediction: there is only 6 accelerometers fixed on engine when factory testing, and there is only 1 vibration sensor used for airborne on-time monitoring in the case of vibration measurement of overall machine. The rotor system cannot be measured directly yet. And the blades, discs and other important structures only can be tested on specially designed test-rigs.

Recently, the fiber-Bragg based temperature and strain measurement as a new sensor technology are investigated. It is proved that the fiber grating sensors have better linearity, repeatability and accuracy than traditional gauges.

***Example* 1: measurement of blade strain in operating condition**

In order to monitoring blade vibration or crack in operating condition for a compressor, directly sensor technologies with the help of optical fibers are achieved. The test system and the blade are shown in Fig. 19.

Fig. 19. The measuring system of blade vibration and crack

Because blade crack signals are often very weak, the identification of crack failure is of great significance and the feature extraction for fault prediction needs renewable data processing methods. The feature frequency of the blade crack is identified by the strain measurement results. As shown in Fig. 20, the crack characteristic frequency of the blade is 53Hz, which is no direct relation with the rotational speed. There is no such a corresponding characteristic frequency happening on a health blade.

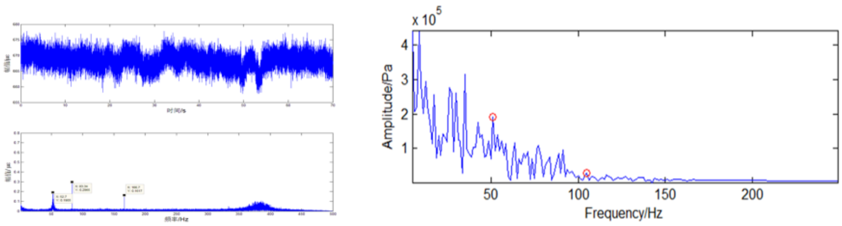


Fig. 20. The measured strains of blade and its feature frequency of crack

***Example* 2: Fiber-Bragg based measurement on bearing operating condition**

There are 6 and 3 fiber Bragg grating (FBG) points are arranged respectively on the outer surface and the inner surface of the inner ring to measure temperature strain distributions. The inner ring fibers pass through the spindle hallow and connected by using of a rotating fiber ring. The FBGs and sensing system are shown as Fig. 21. Different temperature and strain values are measured at different positions of the inner and outer rings, as shown in Fig. 22.

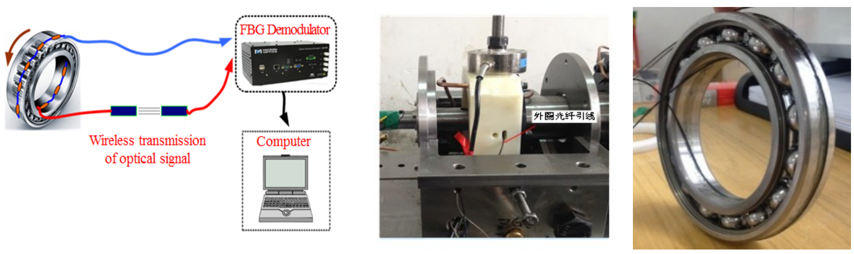


Fig. 21. FBG sensing system and tested bearing

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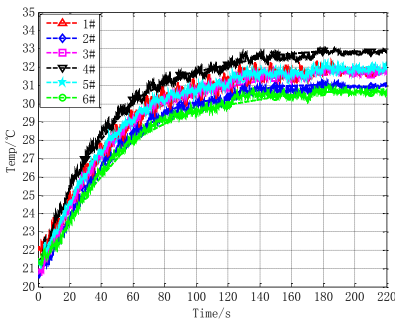
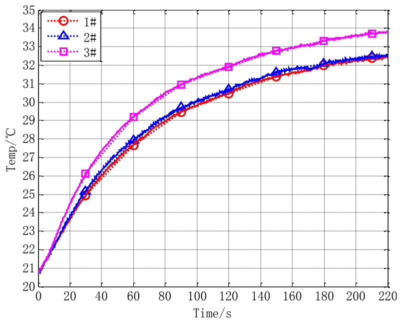
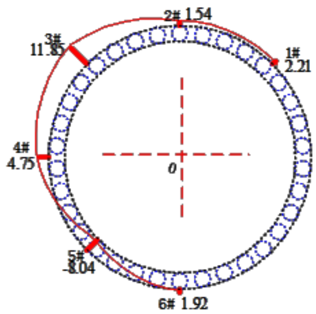


(a) measured temperatures on outer ring



(b) measured temperatures on inner ring



(c) measured strains on outer ring

Fig. 22. Measured data at different positions of the inner and outer rings of a bearing

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

***Example* 1: Kurtosis value changes due to bearing damage**

A rotor test-rig supported by two bearings shown in Fig. 23.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. 24.

Fig. 23. A rotor test-rig supported by two bearings

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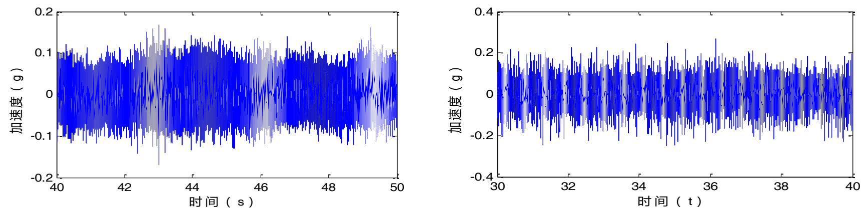
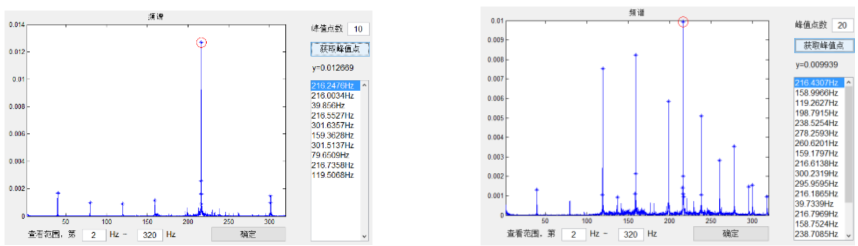
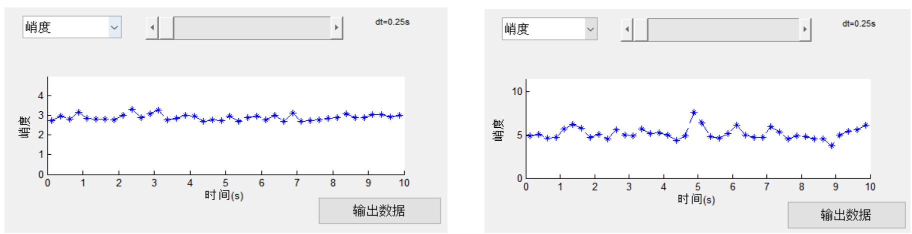


(a) Vibration of normal bearing (b) Vibration of damaged bearing



(c) Spectra of normal bearing (d) Spectra of damaged bearing



(e) Vibration of normal bearing (f) Vibration of damaged bearing

Fig. 24. Vibrations and spectra and Kurtosis value measured on a bearing house

Example 2: Abnormal detection by Kalman filter

The aims of time series analysis are to describe and summarise time series data, fit low-dimensional models, and make forecasts. The Kalman filter is a set of mathematical equations that provides an efficient computational (recursive) solution of the least-squares method. It supports estimations of past, present, and even future states, and it can do so even when the precise nature of the modeled system is unknown.

The time update equations can also be thought of as predictor equations, while the measurement update equations can be thought of as corrector equations, as shown in Fig. 25, which is used for abnormal detection in vibrations of a rotating machinery. The shock happens in a vibration history is detected by using the method of Kalman filter based on ARMA model as shown in Fig. 26.

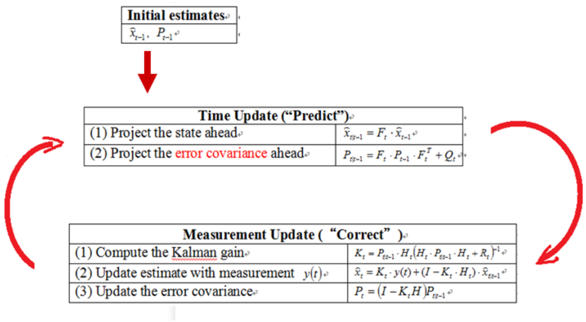


Fig. 24. The flowchart of Kalman filter for detecting abnormal vibration

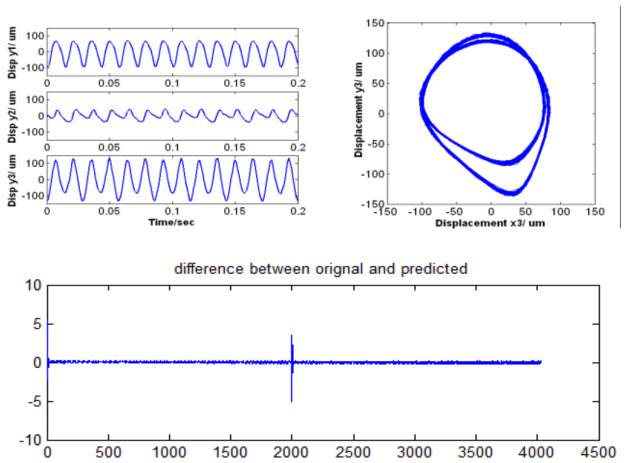


Fig. 25. The time-history of vibration and the detected shock happening inside

***Example* 4: Abnormal Detection by Hilbert-Huang transform (HHT) technique**

In a non-stationary data, it is mostly difficult to make sure of the perfect periods of harmonic components. The averaging method in time domain or wavelet transform with equal frequency bands would bring large errors. In recent years, a novel time-frequency analysis method named Hilbert-Huang transform (HHT) has become popular due to its merits such as uniform resolution at the low- and high-frequency parts, ability to deal with the signals of large size, and so on (Huang, 1998). The technique works by performing a time adaptive decomposition operation named Empirical Mode Decomposition (EMD) on the signal; and decomposing it into a set of complete and almost orthogonal components named Intrinsic Mode Function (IMF), which is almost monocomponent. Every IMF component can be amplitude modulation and/or frequency modulation. So, it is powerful to extract the two kind modulations for a non-

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stationary or nonlinear data [8-10].

The measured vibrations of a rotor system shown as Fig. 25 are analyzed by using of HHT to illustrate the ability of distinguishing the vibration patterns in time-frequency-domain, and the obtained IMFs and EMDs are quite different obviously, as shown in Fig. 26.

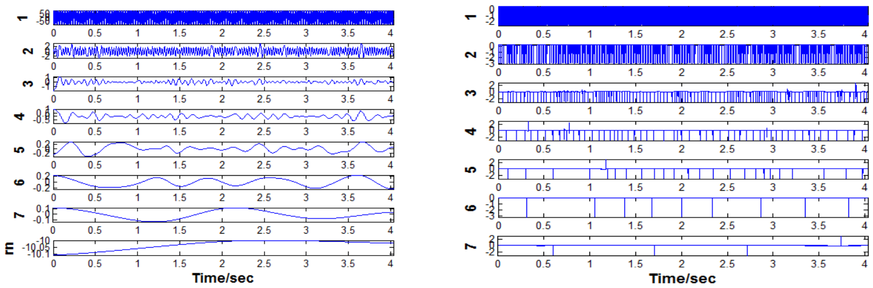


Fig. 26. IMFs and EMDs calculated by HHT for two different vibrations

7 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.

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.

***Example* 1: Expert system (ES) based diagnosis for bearing faults**

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. 27. The interface of the software of it is as Fig. 28.

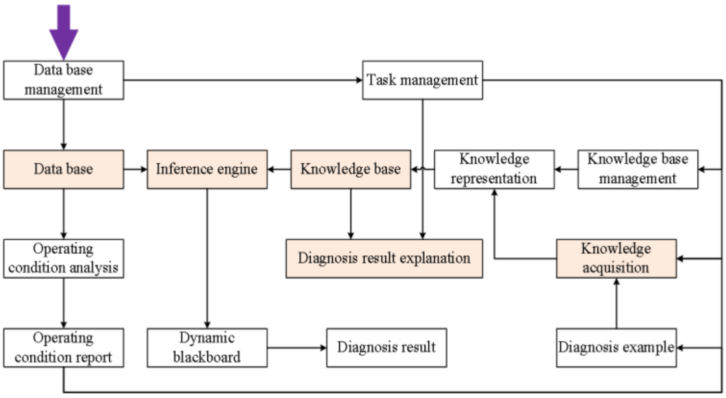


Fig. 27. Framework of an ES based fault diagnosis for bearing faults

Fig. 28. Interface of an ES based fault diagnosis for bearing faults

***Example* 2: Fault-tree based diagnosis**

A basic fault tree of a steam turbine generator set is set up, as shown in Fig. 29, and used during the process of fault identification. The typical rule of deducing of a fault as follows [11, 12]:

Rule2=(Fundamental frequency vibration

(if vibration power frequency fault component contributes more than 60% of pass frequency amplitude 0.95;

amplitude obviously increase when passing critical speed, and phase change is bigger than 100 0.8；

speed stabilizing, phase does not vary with time and load 0.8)；

(then Unbalance fault 0.9))；

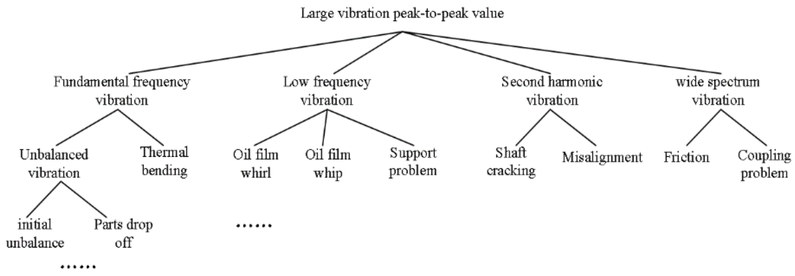


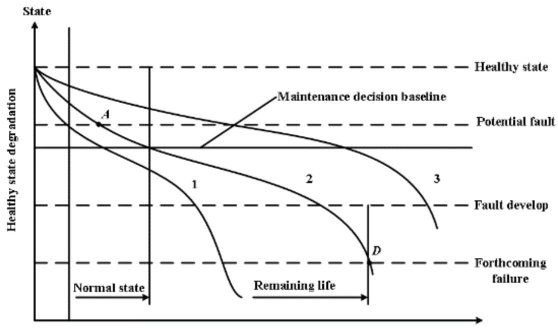
Fig. 29. Fault tree of a steam turbine generator set

8 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.

The definition of health degradation is illustrated as Fig. 30 [2].



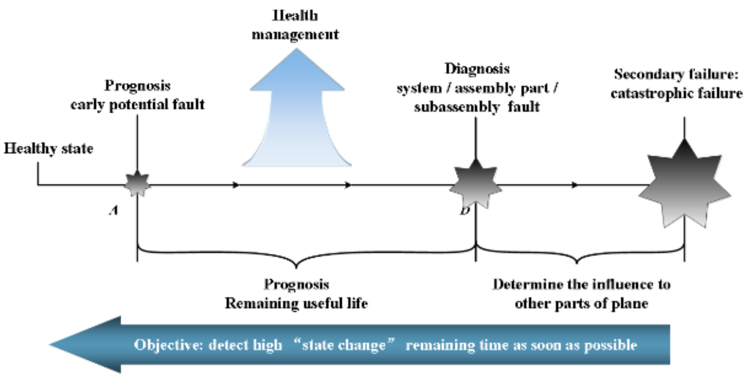
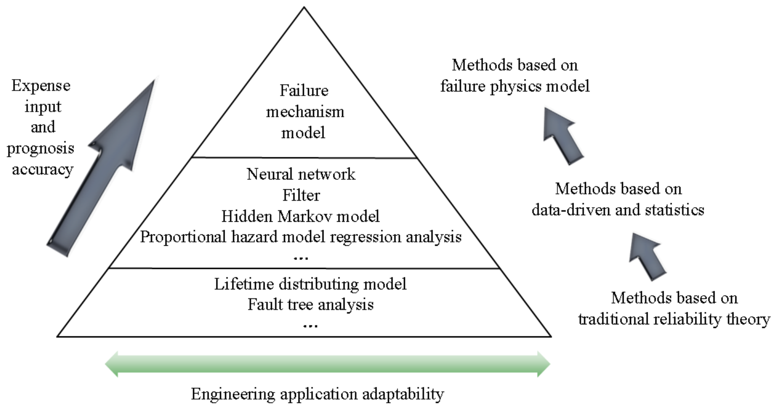
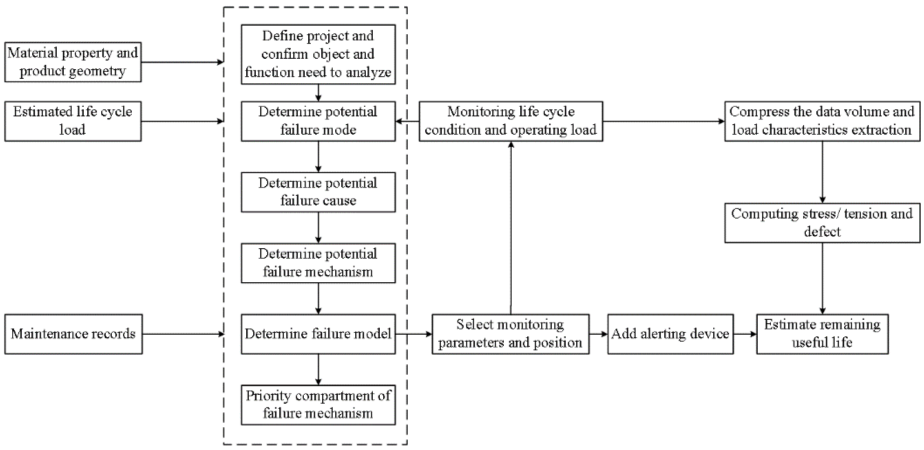


Fig. 30. Definition of health degradation and fault prediction

The description of fault prediction methods is illustrated in Fig. 31 [2].



(a) Methodology



(b) Fault prediction method based on failure physical model

Fig. 31. Fault prediction methods

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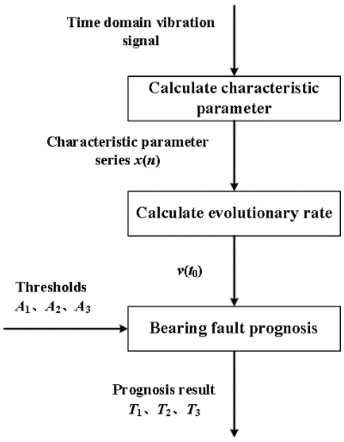
***Example* 1: Bearing crack fault prognosis based on evolutionary rate of characteristic parameters**

The fault prognosis flowchart of a bearing fault is shown as Fig. 32. Based on the measured vibration data of the bearing on the test-rig of Fig. 23, the crack happening and propagating time is predicted, as shown in Fig. 33.



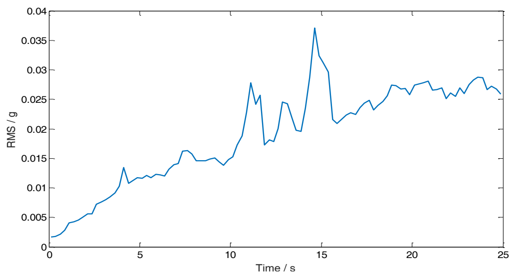


Fig. 32. Fault prognosis flowchart **Fig. 33.** RMS of bearing with inner ring crack

In Fig. 33, abnormal condition determination threshold A_1=0.015, fault condition determination threshold A_2=0.020, failure condition determination threshold A_3=0.030 are set empirically. Using evolutionary rate $v(t_0)$, the prognosticated time which the bearing costs for reaching to three states is obtained.

***Example* 2: Bearing fault prognosis based on ARMA model**

Also, the fault prognosis can also be achieved based on ARMA model. The determination of thresholds and the timespan are shown in Fig. 34, and the practical data together with the predicted data are compared in Fig. 35.

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.

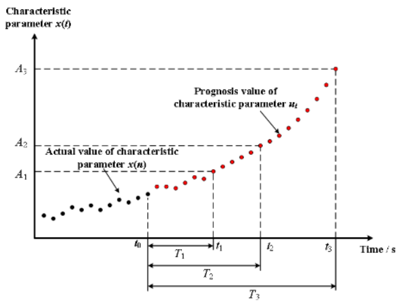


Fig. 34. thresholds and timespan definition

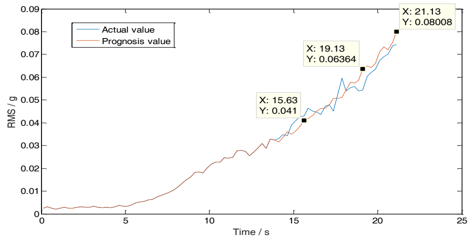


Fig. 35. Bearing cage crack fault prognosis based on ARMA model (p=5, q=8)

9 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

New measurement technology is still developing: high temperature, wireless, network, and so on. Fault detection and prediction are developed based on not only big data but also more intelligent systems.

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