Available online at www.sciencedirect.com
SciVerse ScienceDirect
Procedia Environmental Sciences 10 (2011) 837 – 842
Procedia
Environmental Sciences

2011 3rd International Conference on Environmental Science and Information Application Technology (ESIAT 2011)

Review of Vibration Signals Trend Forecasting Methods

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Abstract

Vibration signals are important information for system failures. Forecasting the trend of vibration signals is an important content of condition monitoring, life estimation and fault diagnosis. The advantages, disadvantages and applicable scope of current trends and main methods on vibration signals forecasting, including time series analysis, grey prediction, ANN (artificial neural networks), SVM (support vector machine) are reviewed in this paper. Difficulties and problems existing in vibration signals forecasting and further research directions, including nonlinear and non-stationary signal processing, combining forecasting method, information fusion technology are then put forward. Finally, this paper proposes that the above methods and prospects should be developed into software system for engineering application.

Keywords: Vibration signals; Trend forecasting; Time series; Grey prediction; ANN; SVM

1. Introduction

Vibration signals of the mechanical system are important information to reflect the system failure. It's important to detect the dynamic mutation of vibration signals to find the early failure of system on time during the process of condition monitoring and failure diagnosis.

FAF (Fail and Fix), the traditional basic concepts of equipment condition monitoring and fault diagnosis, cannot completely guarantee the regularity, efficiency and safety of the system in operation. While, theories and technologies based on PAP (Predict and Prevent), PDA (Performance Degradation Assessment) and FP (Fault Prediction) have been increasingly emphasized in theory and engineering field,

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doi:10.1016/j.proenv.2011.09.135

because that they can achieve the purpose of taking preventive measures to avoid the occurrence and developing of equipment failure.

2. Review of main methods of trend forecasting

2.1. time series analysis method

Time series analysis method firstly arrange the historical data of the object at a certain time interval to construct a time-varying series based on the vibration signal monitoring, and then establish the model describing the changes of data over time to predict the future data for estimation of the spread and development trends of the equipment failure. AR model, MA model and ARMA model are the commonly used time series analysis methods. And all of them, ARMA model is the most perfect in theory and application by far. Its general expression is

$$\overline{Z}_t - \phi_1\overline{Z}_{t-1} - \phi_2\overline{Z}_{t-2} - \cdots - \phi_p\overline{Z}_{t-p} = a_t - \theta_1 a_{t-1} - \cdots - \theta_q a_{t-q} \tag{1}$$

In the model (1), $\overline{Z}_t$ is the regression of its own past values, p represents the number of order; $\phi_1, \phi_2, \cdots \phi_p$ are called autoregressive coefficients, a_t is a white noise sequence with zero mean value and σ_a^2 is variance, which contains q weight coefficients $(\theta_1, \theta_2, \cdots, \theta_q)$. And one step forecast is expressed as:

$$\overline{Z}_{t+1} = \phi_1\overline{Z}_{t-1} + \phi_2\overline{Z}_{t-1} + \cdots + \phi_p\overline{Z}_{t-p+1} - \theta_1 a_t - \cdots - \theta_q a_{t-q+1} \tag{2}$$

When the actually measured data is not stationary time series, the measured data should be converted into a stationary time series before the correct mathematical model can be built. The conversion process is usually complicated, including separation of trend, seasonal items and converting non-stationary series into a stationary sequence corresponding ARIMA, IMA and other models. ARIMA model was used to preprocess the non-stationary time series data, which was converted into standard normal stationary time series. The predicted results are validated by the measured on-site data, and it shows that the AR model fits the time series vibration signals well and the predictive accuracy meets the forecast requirements. Based on vibration signals, linear ARMA model is combined with nonlinear GARCH model to predict health status of machinery [1].

Time series analysis methods highlight the role of time in predicting, without considering the impact of the specific factors of external environment. These models are commonly used in the predictions of vibration series with slow change or ordinary stationary series. Good results can be achieved using time series analysis method if the factors that impact the object do not suddenly mutate. And in short-term forecasts, the results are better. But there will be large deviations if the factors have big changes. Traditional time series analysis method can not effectively simulate the nonlinear characteristics, and is lack of a comprehensive model applicability test criteria.

2.2. grey prediction

General form of the grey model is described as $GM(n, N)$, in which n is the order of the grey differential equation, and N is the number of variables in the grey differential equation. A system that has uncertain connotation or extension is called a grey system. Generation and development of the failure of mechanical system have uncertain factors, which can be thought as a grey system. The principle of using grey theory in forecasting is that the forecasting system is seen as a grey system, and the uncertain 'small samples', 'poor information' system as research object, and to use the existing known information to determine the characteristics, status, development trend of the unknown information with failure mode, forecasting and making decisions for the future failure development. $GM(1,1)$ is the most practical grey forecasting model. For the original series $x^{(0)}$, $x^{(0)} = \{x^{(0)}(1), x^{(0)}(2), \ldots x^{(0)}(n)\}$, after a cumulation, it produces, $(1-AGO)$. And then we can get $x^{(1)} = \{x^{(1)}(1), x^{(1)}(2), \ldots x^{(1)}(n)\}$, in which, $x^{(1)}(k) = \sum_{i=1}^{k} x^{(0)}(i)$. The effect of bad data in the original series has been weakened after the cumulation. The $x^{(1)}$ can be used to form the following one-order differential equation:

$$\frac{dx^{(1)}(t)}{dt} + ax^{(1)}(t) = u \tag{3}$$

In equation (3), a is the development coefficient of the model, reflecting the development trend of $x^{(1)}$ and $x^{(0)}$, and u is the coordination factor of the model, reflecting the changing relationship of different data. The model parameters are solved using least mean square method. Grey model system correlation analysis method, analyzes the trend of raw data, weakens the randomness of the original series, and looks for the rule by raw data processing, while does not use the law of probability and statistics based on large size samples, which is favorable for un-stationary random process. $GM(1,1)$ has been improved in many aspects such as generation method of raw data, model improvement, parameters optimization and so on to adapt to the applications in different areas. There are several typical grey prediction models: equal dimension $GM(1,1)$ model, equal dimension grey filling model and equal dimension innovation model.

A static $GM(1,1)$ model and a dynamical $GM(1,1)$ model are introduced to predict the vibration status of well submersible pump unit in operation of some oilfield [2]. It proved that the accuracy of the two models are both more than 98 percent, and that the prediction errors are both less than 5 percent. It also shows that the dynamical model has better results for its tracking features.

Grey prediction method also has some disadvantages. For instance, the selection of model has great effect on the accuracy of fitting. Lacking abilities of self-learning, self-organizing and adaptive, it is not suitable for approximating complicated non-linear function, especially for systems with volatility and finally the prediction accuracy gets lower as the extrapolation time grows.

2.3. Artificial neural network

For a non-linear autoregressive model (1), expectation of Y is

$$E(Y) = E[f(\theta, X) + \varepsilon] = E[f(\theta, X)] = f(\theta, EX) = f(\theta, X) \tag{4}$$

If function $f(\bullet)$ and parameter θ are known, then Y can be estimated with X. If function $f(\bullet)$ can be realized by neural network, for its strong nonlinear mapping ability, the time series can be predicted as the formula:

$$y = x_{M+1} = h\left[\sum_{n=1}^{N} \omega_{nJ}^{2} f\left(\sum_{m=1}^{M} \omega_{mI}^{1} x_m + b_I^1\right) + b_J^2\right] \tag{5}$$

Levenberg-Marquardt BP network is used in complicated nonlinear vibration response forecasting [3]. And Box-Cox transform is introduced to improve convergence and the convergence rate of the network; repeated training method is used to improve the stability and prediction accuracy of the network.

Artificial neural network has the following advantages:

- Can approximate arbitrary nonlinear function;
- Has parallel processing ability and forecasts fast;
- Good fault tolerance, good robustness, and high forecasting accuracy;
- Can deal with problems that cannot be solved with conventional information processing methods.

Meanwhile, the network training needs large amounts of data samples and the network structure is hard to determine, the calculation speed is slow and the net mapping is invisible. When the network is used to simulate a time series, the accuracy cannot be guaranteed if the number of hidden layer nodes is too small. Contrarily, if the number is too large, the training progress will easily fall into local minimum. Therefore the selection of an optimal network structure with performance not reduced is the key to neural network design.

2.4. Support vector machine

$$f(x) = \omega \cdot \phi(x) + b = \sum_{i=1}^{k} (\alpha_i - \alpha_i^*) k(x, x_i) + b \tag{6}$$

Shock, vibration mutation, structure deformation, friction changes existing in the mechanical system process lead to the non-stationary and non-linear characteristics of the system vibration, which make it hard to analyze the variation rule of the system with the experiment data.

In (6), the goal of support vector machine is to get the optimal solution under the existing information, specifically for the limited sample of cases, but not only when the sample tends to infinity. It has been systematically studied in theory that the principle of empirical risk minimization, relationship between empirical risk and expected risk for limited samples data, as well as theory and realization method of SRM (structural risk minimization) principle. Based on SRM, SVM is different from neural network and other conventional methods. SVM aims to minimize the range of confidence with the training error as the optimization constraints, instead of trying to minimize the training error. The generalization ability of SVM is significantly superior to the traditional learning methods. In addition, SVM converts the practical problems to high-dimensional feature space by a nonlinear transformation, and constructs linear discriminant function in high dimensional space to achieve nonlinear discriminant in the original space, which guarantees the good generalization of SVM, and solves the problem of the curse of dimensionality, making the algorithm complexity independent of sample dimensions, and eventually transforming the practical problem into a quadratic optimization problem, which in theory, will give a global optimum.

The indicator of prediction evaluation is the root mean square error. Single-step prediction predicts the next time data based on the established single-step prediction model and data before time t, while multi-step prediction predicts next multi-time data with the current data. And experiment was carried out with typical Lorenz nonlinear system data in the former research. It showed that SVM still had high accuracy as the number of prediction steps increases. Moreover, a new time series analysis method is introduced based on support vector regression [4]. And smoothing method was used to improve the new method, reducing the computational complexity degree. The method was then applied to establish the steam turbine vibration model with the turbine vibration data sequence. It showed that this method had good predictive ability.

SVM is based on VC-dimension theory and structure risk minimization principle. It does not only solve the problems of small sample, over learning, high dimension and local minimum, but also has stronger generalization ability, providing a new effective way for time series forecasting. The main idea of SVM is mapping a nonlinear problem in input spatial into a linear problem in high dimensional feature space, which makes it suitable for complicated nonlinear, non-stationary time series trend forecasting. Therefore, it plays a prominent role in long-term status forecasting of large and complex machinery. However, the selection of SVM kernel function is a difficult problem, and has no theoretical guidance.

3. Conclusions and further research directions

3.1. Difficulties

In recent years, applications in diagnosis and prediction of aviation engines have got many satisfactory results, especially for large aircraft engines. However, because of the complex structure of engine, the many excitation sources unsmooth running and multi-source signals mixing, its practical application has not yet achieved satisfactory results. The difficulties mainly are the following three aspects [5]:

- Information poorness of data. Vibration information of aircraft engines is complex, incomplete, not comprehensive and uncertain, with which diagnosis and vibration forecasting have been primary problem.
- Features selection. It has been the key to condition trend prediction how to select the important features and parameters that can fully describe the operating states and conditions of the aircraft engines, without causing information and data redundancy.
- Research on forecasting methods. It's difficult to select the proper forecasting method for aircraft engines, for the different complexity, data requirements and prediction accuracy of different methods.

3.2. Combination with nonlinear and non-stationary signal processing

In engineering practice, the measured vibration signals of aircraft engine are full of diversity, large amounts of which are non-stationary, non-Gaussian distribution and nonlinear random ones. In the field of reliability prediction for aircraft engine, methods suitable for status signals processing and extraction of parameters of life characteristics are developed from the generally used signal processing methods, which are the prerequisite for the all forecasting, and also the basis for various forecasting methods. If the information reflecting the state of the equipment was not detected and processed or the characteristic parameters of life cannot be extracted, there would have been no way of making the life prediction. Thus, the forecasting has combined more and more tightly with the nonlinear and non-stationary signals processing. For example, Wang and Zhu (2008) discussed the trend forecasting of non-stationary vibration signals based on EMD and LS-SVM [6].

3.3. Composite prediction methods

Curve fitting is simple and intuitive, but the prediction results are easily affected by the recent data, which makes it not suitable for prediction of multi-factor, and have less nonlinear fitting ability. The number of sample required for time series analysis is bigger, and good forecasting results can not be achieved without proper model. The results of grey prediction method are not unique, and the accuracy is affected by the selection of model. And neural network algorithm is complex, and the forecasting model can not be expressed by formula. Therefore, it is hard to predict status trends of the hypersonic vehicles with poor information and uncertain conditions using a single predictive model. Cluttered work environment of hypersonic aircraft leads to the complex changes of system vibration, with many external factors affecting, such as time-varying, random, fuzzy and so on. In order to fully utilize the advantages of different predictive model, composite prediction methods can be formed with a certain consolidated synthesis of different methods, which can use all the useful information, effectively improve the fitting ability of the model, and make up for shortages of a single model approach to improve the prediction accuracy. For example, Cui, Hong and Zhao (2010) introduced a combining series integrated model of grey prediction and neural network forecasting method, which integrated both of their own characteristics and good complementary characters [7].

3.4. Combinations with information fusion

Multiple sensors in different positions can be used simultaneously to monitor various parameters such as vibration, noise, temperature, pressure, and flow, to monitor the aircraft engine in full range and multi-angle. It can solve the difficulty of lacking vibration information, with the application of information fusion in the extraction of the fault feature that fully reflects the operating status during the process of achieving the characteristic parameters. Short term real-time monitoring is performed with the key components of mechanism and long term off-line prediction is performed with its overall performance, which achieves monitoring and forecasting with full range of time and space. And aiming at the difficulty of extraction of state features, condition monitoring and trend forecasting will organically combine for a comprehensive analysis of the relevant parameters to reflect the mechanical equipment operating status and overall performance and provide evidence for the prediction of remaining life of mechanical equipment.

3.5. Developments of software and hardware systems

Research should be made on the common failure problems of the mechanical system, then the modular of diagnosis and the prediction can be introduced. Diagnosis and prediction module library of components that have the same structure characteristics and operational parameters or have similar failure mechanism and manifestations should be established. Thus, diagnosis and prediction of different models, and complex engine can be done with the corresponding parts module combined, saving significant development costs and time. With computer and network technology developed rapidly, computer technology enables automation and intelligence of diagnosis and prediction, and network technology enables remote monitoring, controlling and resource sharing.

For the aircraft engine control system, vibration signal trend prediction algorithms can be designed as digital filters, which are solidified into the FPGA, DSP in order to achieve real-time forecasting and controlling.

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