A Fault Diagnosis Technique Based on Nonlinear Spectral Analysis and Its Application in Electric Rudder

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Abstract – *a fault diagnosis technique based on nonlinear spectral analysis was introduced and was applied into a certain helicopter's electric rudders in this paper. One distinguishing feature of this technique is that it can not only diagnoses the faults which have become serious and dangerous but also can forecasts the potential faults when they are till in their early developments. Lots of experiments have shown that this fault diagnosis technique has a higher accuracy in fault forecasting and diagnosis, meanwhile, only limited calculating quantity and store spaces are needed. This technique is very appropriate for on-line fault diagnosis, and may have great significances in the electric rudder's and other large class of mechanical systems' fault diagnosis.*

Keywords: nonlinear spectral analysis, electric rudder, fault forecast and diagnosis, generalized frequency response functions (GFRF's).

1.Introduction:

Being the executor of helicopter's manipulation system, electric rudder, composed of electromotor, gear reducer and stress spring, etc., plays a great important role in ensuring the safety of helicopter's flying. Once some faults have happened with electric rudder, whether the faults are latent ones or not, helicopter's flying may be becoming very dangerous and sometimes disasters may be led, because electric rudders connect directly to helicopter's manipulation system. So to keep both the obvious faults and latent faults from the electric rudder becomes very important.

It is well known that most of latent faults are caused by the gradual changes in components of the diagnosed objects, such as the aging of electromotor, stress spring, detent failure and so on. So, finding a fault diagnosis technique which can not only detect out the obvious and serious faults but also can find out the potential ones and give timely forecasts correctly becomes very necessary and significant in preventing any dangers or calamities aroused by the faulted rudder from helicopter completely.

Because these gradual changes mentioned above are usually reflected by the changes in the nonlinear part frequency spectrum of the diagnosed object then, if the frequency spectrum's changes are sensitive to the changes in the mechanical transition properties, an efficient fault diagnosis method for mechanical systems is using the nonlinear spectral analysis technique introduced in this paper. The mean idea of this fault diagnosis technique is just to identify the generalized frequency response functions (GFRF) of the diagnosed object [1,4], and a diagnosis result can be worked out by comparing the changes between the current frequency spectrum and the normal ones which have already been obtained from a equivalent system which works well.

In this paper, this fault diagnosis technique was applied to a certain helicopter's electric rudders, and after many times' experiments we found its higher accuracy in fault forecasting and detecting, and its simplicity in calculating and store space saving, all these features make this technique very appropriate for online fault forecasting and detecting.

2. Nonlinear spectral analysis for electric rudder

2.1 Generalized Frequency Response Function

For SISO time-invariant casual nonlinear system, its output $y(t)$ can be represented by the Volterra series as [5]

$$y(t)=\sum_{n=1}^{\infty}y_n(t)=\sum_{n=1}^{\infty}\int_{-\infty}^{\infty}\cdots\int_{-\infty}^{\infty}h_n(\tau_1,\ldots,\tau_n)\prod_{i=1}^{n}u(t-\tau_i)d\tau_i \quad (1)$$

where $\{h_n(\tau_1,\tau_2\ldots\tau_n),n\in N\}$ are the Volterra time-domain kernels or the generalized impulse response functions. Taking multi-dimension Fourier transform to the above equation may yield ones as:

$$\hat{y}(\omega)=\mathrm{F}(y(t))=\sum_{n=1}^{\infty}\mathrm{F}(y_n(t))=\sum_{n=1}^{\infty}\hat{y}_n(\omega)$$

$$\hat{y}_n(\omega)=(2\pi)^{-(n-1)}\int_{-\infty}^{\infty}\cdots\int_{-\infty}^{\infty}\hat{h}_n(\omega-\omega_2-\cdots-\omega_n,\omega_2,\ldots,\omega_n)$$

$$\cdot\hat{u}(\omega-\omega_2-\cdots-\omega_n)\cdot\hat{u}(\omega_2)\cdot\cdots\cdot\hat{u}(\omega_n)d\omega_2,\ldots d\omega_n, \quad (2)$$

where, $\hat{h}_n(\omega_1,\omega_2\ldots\omega_n)$ is the n-dimensional Fourier transform of $h_n(\tau_1,\tau_2\ldots\tau_n)$ for $n\in N$, which are called the generalized frequency response functions (GFRF's),i.e.,

$$\hat{h}_n(\omega_1,\ldots,\omega_n)=\mathrm{F}(h_n(\tau_1,\ldots,\tau_n))$$

$$=\int_{-\infty}^{\infty}\cdots\int_{-\infty}^{\infty}h_n(\tau_1,\ldots,\tau_n)\prod_{i=1}^{n}e^{-j\omega_i\tau_i}d\tau_i$$

It is clear that $\{h_n\mid n\in\mathbf{N}\}$ and $\{\hat{h}_n\mid n\in\mathbf{N}\}$ are all the nonparametric model of nonlinear system. Just as the impulse response function of linear system, they can describe the essential properties of the nonlinear system and do not dependent on the kind of input signals.

2.2 the simplicity of the identification of GFRF's

The identification of GFRF's is more complicated because there should be infinite terms of GFRF's to describe a system completely according to the Volterra functional series theory. And the scale of data needed in the identification will be increased exponentially with the system's order and degree increasing. This is so called "dimension catastrophe problem".

So, in order to solve this difficulty we introduced a simplified algorithm [1], which can solve this difficulty and meanwhile, keep a high accuracy both in fault forecasting and diagnosis.

Some assumptions are made for this simplified algorithm as follows:

First, the input signal is a linear combination of sine signals that designed artificially, each of all the sine signals' frequency components is times of the basic frequency. And the input and output signals should be sampled synchronously.

Second, the dynamic behavior of the system can be described approximately with the first three order GFRF's.

And according to the symmetric and conjugate symmetric properties, it is assumed that all the GFRF's have the same value in the hyperplane, $\omega_1+\omega_2+\cdots+\omega_n=\omega$.

Under all the assumptions mentioned above, a simplified functional equation can be obtained as below:

$$\begin{aligned}Y(k\omega_0)&=H_1(k\omega_0)U(k\omega_0)+\frac{H_2(k\omega_0,0)}{N_s}\sum_{s=0}^{N_s-1}U((k-s)\omega_0)U(s\omega_0)\\&+\frac{H_3(k\omega_0,0,0)}{(N_s)^2}\sum_{s=0}^{N_s-1}\sum_{\tau=0}^{N_s-1}U((k-s-\tau)\omega_0)U(s\omega_0)U(\tau\omega_0)\\&=H_1(k\omega_0)U(k\omega_0)+\frac{U(\omega_0)*U(k\omega_0)}{N_s}H_2(k\omega_0,0)\\&+\frac{U(\omega_0)*U(\omega_0)*U(k\omega_0)}{(N_s)^2}H_3(k\omega_0,0,0)-----(3)\end{aligned}$$

Where, $k=-3Nr+3,\ldots,-1,0,1,\ldots,3Nr-3$, and $N_r\omega_0$ is the cutoff frequency of the input signals, and the N_s is the sampling length of the output signals, $N_s=kN_r,k\in N$, and $N_s\omega_0$ is according to the max frequency band-width.

According equation (3), we can find that only three times experiments are needed in solving the equation groups which are made up of deficiency equations.

3.nonlinear spectral analysis of electric rudder

3.1 the principles of the fault diagnosis based on nonlinear spectral analysis

The principle of fault diagnosis based on nonlinear spectral analysis can be described as follows. Firstly, the GFRF's feature database of the electric rudders should be built up according to a lot of standard GFRF's sample data. And then for the diagnosed rudders, the input signal and the output signal should be sampled synchronously, so that the current 1st, 2nd and 3rd GFRF of the electric rudder can be estimated by using the sampled input and output data.

And fig.1 shows the process of data sampling. Where, f(t) is the work signal needed by the electric rudder, x(t) is the artificially designed sine combined signal which is a persistent exciting signal needed for the identification of the electric rudder's GFRF's model, u(t) is the actual input signal to the electric rudder, y(t) is the actual output signal, n(t) is the observe noise and z(t) is the final observed value.

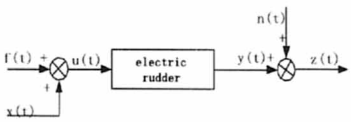

fig1:rudder data sampling

After the current GFRF spectrum features have been extracted by using pattern recognition technique, the current state of the electric rudder can be diagnosed immediately, and if the rudder has potential faults timely forecasts will be given.

In this fault forecasting and diagnosis system, we can see that three steps are most important: GFRF's identification, feature extraction, and pattern recognition. The faults forecasting and diagnosis framework is shown below.

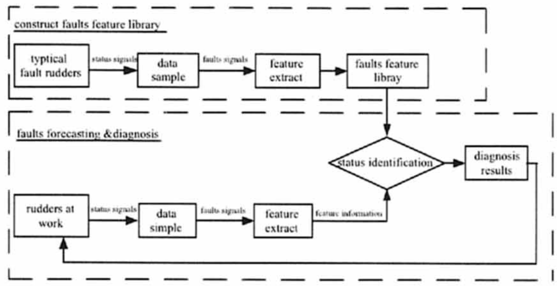

fig2:faults forecast & diagnosis framework

3.2 Feature Extraction

Although there are many different features for mechanical fault diagnosis systems, for a practical system, the available features should be determined according to the application environment, object properties, and implementing convenience, etc. Because of the complexity of GFRF's spectrum of nonlinear system, the GFRF's spectrum features should be extracted from the magnitude of GRFR's spectrum, which are considered as follows:

For 1st order GFRF, take

$$\hat{H}_1(k) = H_1(k), \quad k = 0,1,\ldots,N-1 ----------(4).$$

For 2nd order GFRF, take

$$\hat{H}_2(k) = \frac{1}{N}\sum_{r+s=k} H_2(r,s), \quad k = 0,1,\ldots,2N-2 -------(5).$$

For 3rd order GFRF, take

$$\hat{H}_3(k) = \frac{1}{N^2}\sum_{r+s+t=k} H_3(r,s,t), \quad k = 0,1,\ldots,3N-3 ---(6).$$

According to equation (4)~(6), GFRF's spectrum magnitude features can be extracted. And the state patterns of the electric rudder can be classified by using a certain pattern recognition technique.

3.3 Experiment results

we applied the simplified algorithm into the identification of the electric rudder's GFRF's and plot their amplitude spectrum which are showed as figure3 and figure4, where figure3 illustrates a well worked electric rudder's amplitude spectrum of the 1^{st}, 2^{nd} and 3^{rd} order GFRF, meanwhile, figure4 shows the according amplitude spectrum of a electric rudder, which has faults caused by the aging of the electromotor which drives the electric rudder.

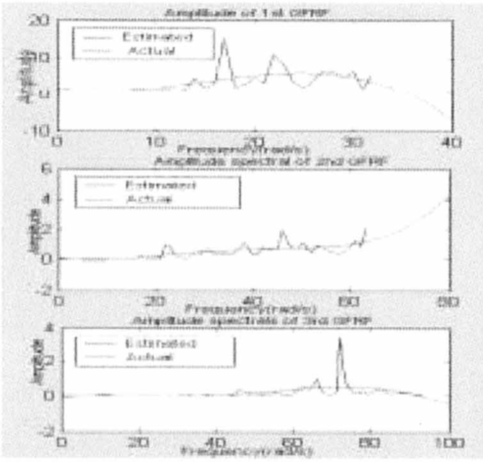

fig.3. spectrum of normal working rudder

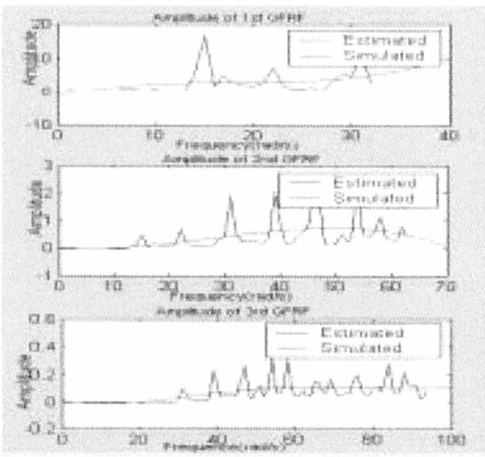

fig.4. spectrum of fault rudder

by comparing fig.3 and fig.4, we can find that, the normal electric rudder's amplitude of 2^{nd} and 3^{rd} GFRF's are not very high; however when the rudder has a fault caused by the aging of the electromotor, its nonlinear part spectrum, that is the 2^{nd} and 3^{rd} GFRF's, have higher amplitudes. So, we can draw a conclusion that the rudder's essential transmission property have been changed, and that a latent fault may have happened in its early time.

4.Conclusion

This fault diagnosis technique has a distinguishing feature that it can forecast potential faults and then can prevent the diagnosed system from any faults completely. Meanwhile this technique's simplicity in calculation and high accuracy in fault forecasting made it great significant in the fault diagnosis of the electric rudder and other mechanical systems.

References

[1] Chongzhao Han, Liqi Wang, Xiaoquan Tang. Identification of Nonparametric GFRF Model for a Class of Nonlinear Dynamic Systems. Control Theory and Applications, 1999, Vol. 16(6): 816-825.

[2] Billings S A and Tsang K M.Spectral analysis for nonlinear systems, Part I: parametric nonlinear spectral analysis. Mechanical System and Signal Processing, 1989, 3(4): 319-339

[3] Billings S A and Tsang K M.Spectral analysis for nonlinear systems, Part II: interpretation of nonlinear frequency response functions.Mechanical System and Signal Processing, 1989, 3(4):343-359

[4] xiaoquan Tang. Nonlinear Spectral Analysis and Its Applications in Fault Diagnosis, Journal of Xi'an Jiaotong University, 1999.

[5] M. Schetzen, The Volterra and Wiener Theories of Nonlinear Systems. Wiley, 1980.