Health Management System Design Method for the Helicopters' Gyroscope Based on Intermittent Fault Features and Built-in Test

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***Abstract*—In recent years, the method of time stress monitoring to improve the ability of fault prediction and false alarm recognition has attracted more and more attention. It is found that intermittent failure will increase with the aging of helicopter gyroscope. The time stress of helicopter gyroscope in the process of manufacture, transportation and use is the main reason of helicopter gyroscope aging. The intermittent failure characteristics of helicopter gyroscope can represent its healthy state. This paper briefly introduces the concepts of time stress and health management system. Then, a new design method of helicopter gyro health management system based on intermittent fault characteristics and in-flight testing is proposed. The system structure consists of five modules: sensor module, intermittent fault detection module, permanent fault diagnosis module, permanent fault prediction module and health management module. Finally, the structure and function of each module of helicopter gyroscope health management system are introduced in detail. Experiments show that this method can effectively improve the fault prediction and false alarm recognition ability of helicopter gyroscope.**

Keywords- health management intermittent fault; helicopters' gyroscope; Built-in Test; time stress

I. INTRODUCTION

It has already been realized that the helicopters' gyroscope is always suffered from all kinds of time stress since it was produced. It is found that the main cause of false alarm in the internal test system is the combined time stress [1,2], and the cumulative damage caused by this stress is the direct external factor of the performance decline of the gyroscope. Therefore, it is expected to reduce the false alarm rate of the test system by collecting and analyzing the environmental and working stress. On the other hand, with the aging of helicopter gyroscope, intermittent failure will increase. The intermittent failure characteristics of helicopter gyroscope can reflect the health status of helicopter gyroscope. Therefore, in order to improve the capability of fault prediction and health assessment of helicopter gyroscope, it is necessary to design a health management system. In this paper, a new health management design technique and system structure are proposed based on the in-flight test system based on the intermittent fault characteristics of helicopter gyroscope.

II. AGING PROCESS OF THE HELICOPTERS' GYROSCOPE

It is well known that the gyroscope is the key equipment in a helicopter. Its structure is very complicated, and its hardware is shown in figure 1.

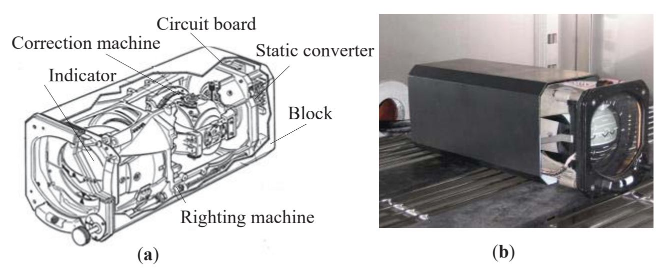

Figure 1. the structure of the helicopters' gyroscope

In practical engineering, it is founded that with the aging of the helicopters' gyroscope, the intermittent fault will grow. For

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example, the numbers, duration and magnitude of intermittent fault increases. The typical evolution of intermittent failure dynamics is shown in Figure 2.

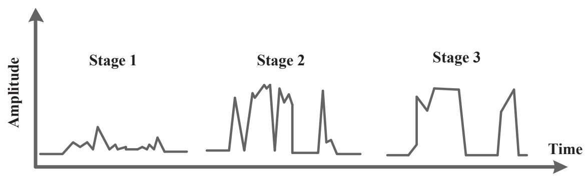

Figure 2. Evolution of intermittent failure dynamics [3].

We know that the intermittent fault features of the helicopters' gyroscope can represent its health state from Figure 2.

III. OVERALL STRUCTURE OF HELTH MANAGEMENT SYSTEM

It is well known that the structure of electromechanical equipment is very complicated, and there are various failure modes. At the same time, because of the adverse working environment, the failure rate of the equipment and the false alarm rate of the BIT system are very high. In order to improve the false alarm recognition and fault prediction capability of the helicopters' gyroscope, we introduce the HM design method which have the time stress collection and intermittent fault detection abilities based on the BIT and TSMD, the overall structure of the HM system for the helicopters' gyroscope is shown in the Fig.3.

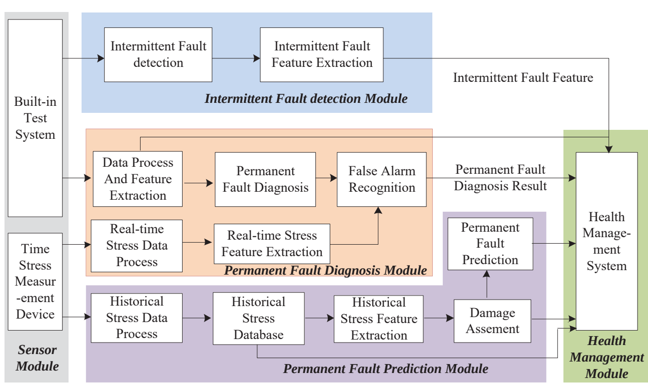

Figure 3. The overall structure of the HM system for the helicopters' gyroscope

As shown in Fig.3, we know that the helicopters' gyroscope HM system includes five modules: sensor module, intermittent fault detection module, permanent fault diagnosis module, permanent fault prediction module and health management module. The working mechanism and implement method of the system is listed as follows:

1) *The sensor module is implemented by adding some time stress sensors, test circuits and devices(TSMD) based on the primary BIT system of the helicopters' gyroscope.*

2) *Intermittent fault detection module is used to detect the intermittent fault response signal and extract the intermittent fault features. These intermittent fault features can be used to assess the health state of the helicopters' gyroscope.*

3) *In order to improve the false alarm recognition ability of the permanent fault diagnosis module, the real-time stress data feature collected by TSMD and the diagnosis result of the BIT system are analyzed synthetically.*

4) *The damage assessment method for the equipment is used to analyze the historical stress data and the failure model of the helicopters' gyroscope. And then, permanent fault prediction process will be performed by combining the damage information of the equipment and the last diagnosis result of the permanent fault diagnosis module.*

5) *All the information collected by the sensor module, ntermittent fault detection module, permanent fault diagnosis module, permanent fault prediction module are sent into the health management module, and willed be analyzed synthetically.*

The structure, design and implement method, functions of each module of this HM system will be described in detail in the follow chapter.

IV. ARCHITECTURE OF MODULES

A. *Sensor module*

Sensor module of the gyroscope's HM system includes the test circuit of the BIT system and various sensors of TSMD. The main function of this module is to collect various components' state information and time stress information. It is the sense apparatus of HM system. The sensor module is an information collection and input system. Firstly, the intermittent fault response signal is catched by BIT circuits, the main stress factors that induce the fault or false alarm of BIT system will be found out, with the help of the failure mode and effects analysis (FMEA) of the gyroscope. Secondly, the effect degree of each stress factor will be obtained by the relation analysis technology such as logistic regression [4]. At last, the general structure of the sensor module is shown in Fig.4 can be acquired based on the distribution of measuring points and sensors.

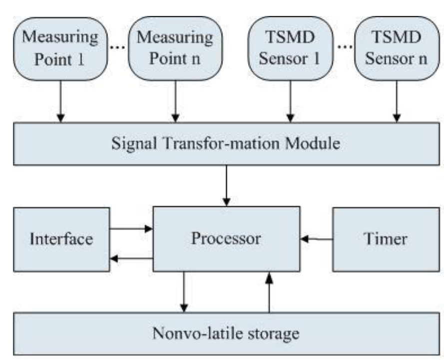

Figure 4. The general structure of sensor module

B. *Intermittent Fault Detection Module*

Intermittent fault detection module of the gyroscope's HM system includes test control, test stimulate source, transient inductors and other circuits. The general structure of the intermittent fault detection module is shown in Fig.5. When there is an intermittent fault occurring , a transient inductor can acquire the week response signal immediately, and then, this signal will be amplified by an amplifier. At last, the intermittent fault will be detected by comparing the amplified signal with the reference source.

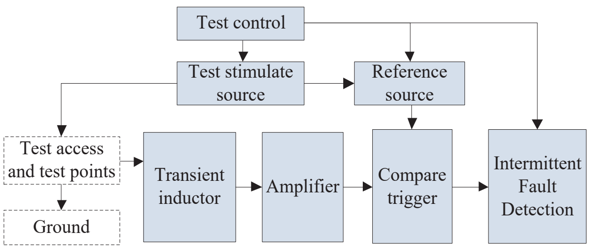

Figure 5. Intermittent Fault detection method

C. Permanent Fault diagnosis module

There is a high false alarm rate in the BIT system of helicopters' gyroscope because of the influence of various environment and working stresses. The high false alarm rate will directly reduce the reliability of the diagnosis result, and it directly affect the application of the BIT system in engineering field. In this paper, the real-time stress data feature collected by TSMD and the diagnosis result of the BIT system are analyzed synthetically, in order to improve the false alarm recognition ability of the fault diagnosis module. There are two support vector machines (SVM) in the fault diagnosis module. One is Fault Diagnosis SVM(FDS), and the other is False Alarm Recognition SVM(FARS). The detailed technical approach of the diagnosis module is shown in Fig.6.

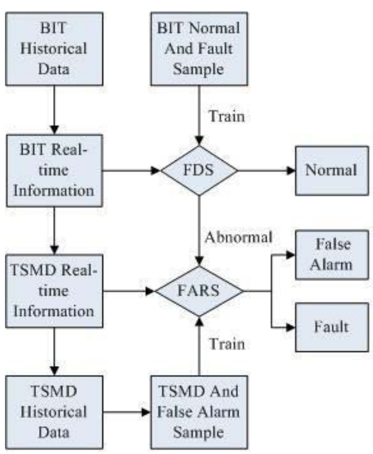

Figure 6. The general structure of fault diagnosis module

As shown in Fig.6, lots of historical data is required to train the FDS and FARS, and then the new sample of BIT or TSMD could be recognized.

D. Permanent Fault prediction module

Generally, the degradation or deviation degree of expected normal state is defined as health condition in engineering, so is the health condition definition of helicopter gyroscope. The method of fault prediction is generally used to evaluate the equipment health condition and determine when the fault occurs. From the definition of health management, we can clearly know that permanent fault prediction system is the key part of health management and the key technology to realize helicopter gyroscope health management system. Intensity, duration and the combination of various temporal stresses (such as temperature, humidity, vibration and radiation) are usually the main factors causing helicopter gyroscope failure. Many fault mechanisms of helicopter gyroscope components and the product fault models related to time stress have great similarity in mechanism. Therefore, we can monitor the time stress of the equipment in its life cycle through the reasonable deployment of sensors, as a basis to evaluate the damage degree of the equipment caused by a certain stress and predict when the equipment may fail. According to the research literature, CALCE ESPC of the university of Maryland proposed a new permanent failure prediction method of electronic products called "life consumption monitoring" [5,6]. In general interpretation, this method is the process of evaluating and predicting the residual life of the equipment. Its core technology mainly involves the continuous or periodic measurement, monitoring, recording and interpretation of physical parameters related to the working environment of the product. This paper designs a new permanent fault prediction module based on the multi-point life consumption monitoring technology and time stress analysis technology. The structure of the permanent fault prediction module is shown in Fig.7.

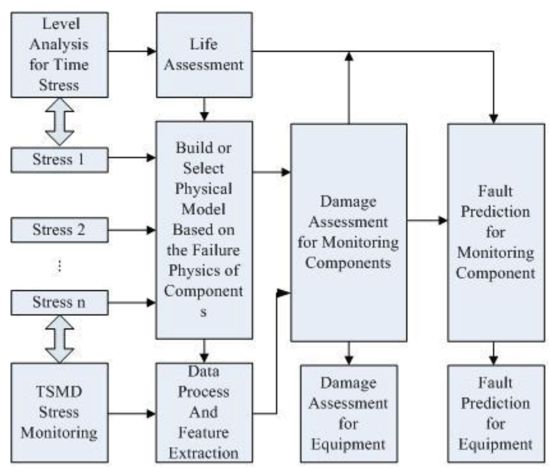

Figure 7. The structure of fault prediction module

1) Descriptive Model of the Damage induced by Time Stress

Through previous studies, we know that time stress (such as vibration, temperature, humidity, etc.) is the main external factor that leads to degradation or deviation from expected normal state of electromechanical system. The accumulation of component damage caused by time stress in the whole life cycle of electromechanical system will lead to more and more failures or functional degradation of the system. Therefore, we know that the main factors causing damage to system components and electromechanical systems are continuous or discontinuous environment and working stress.

Based on the above research results and the discontinuous characteristics of helicopter gyroscope stress monitoring, the time stress process of helicopter gyroscope in its life cycle is divided into several segments, among which, the continuous damage accumulation process is regarded as a dynamic discrete random process. Petri nets have a strong ability to study the dynamic discrete random process, which is mainly used to describe and analyze the control flow and information flow in the system, and can clearly express the state change process of the system [7]. Thus, based on Generalized Stochastic Petri net (GSPN), the dynamic description model of the relationship between the actual damage accumulation process and time stress of helicopter gyroscope components and system is constructed in this paper. The structure of the model is shown in Fig.8.

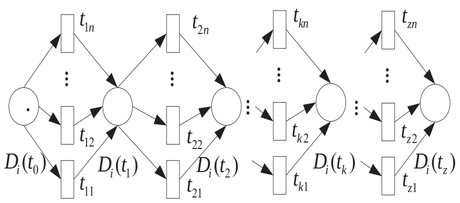

Figure 8. The descriptive model of the helicopters' gyroscope components damage based on GSPN

In Fig.8, $D_i(t_j)$ represents the cumulative damage of the i th component subjected to the j th stress spectrum, and t_{jr} represents the damage change of the stress spectrum of the i th component to the r th component.

2) Damage assessment method based on DM-LCM

Life consumption monitoring (LCM), whose technical core is to use physical failure model to evaluate the life consumption and residual life of products under life cycle conditions, is a prediction method in health monitoring. This method is the main research direction in the field of electronic prediction and health management, proposed by CALCE center for electronic products and systems, university of Maryland [8,9]. It is very important for LCM to build or select a physical model because this methodology is based on the failure physics of the product. Because of the long history of research on failure physics of electronics, it is easily to build the physical model for some element level products such as electric resistance, capacitance, MOSFET, solder joints. Therefore, LCM method is suitable for the research of damage detection of component products. The damage changing process of system-level products is a dynamic random process. It is difficult to establish accurate physical models for system-level products because the components are sensitive to different stresses and damage degrees when they bear different kinds of stresses. Therefore, in order to evaluate system-level damage more accurately, it is necessary to carry out dynamic monitoring of its dynamic random process. In order to improve the accuracy of dynamic monitoring evaluation, a dynamic multi-point life monitoring (dm-lcm) technique based on LCM is proposed. The technical process is shown in Fig. 9.

DM-LCM technology, based on LCM technology, adds new modules such as system FMEA, time stress level analysis, time stress and system fault comprehensive analysis, and system damage assessment. The specific process of DM-LCM includes the following steps:

a) FMEA for the helicopters' gyroscope system

In the design process of helicopter gyroscope, fault pattern recognition, mechanism and effect analysis are mainly adopted to identify potential fault patterns. Meanwhile, FMEA method is adopted to determine the influence of failure mode and the root cause of failure mode. In the DM-LCM process, key components and failure modes of the system can be found through system FMEA, and the mechanism of these failure modes caused by time stress can be analysed.

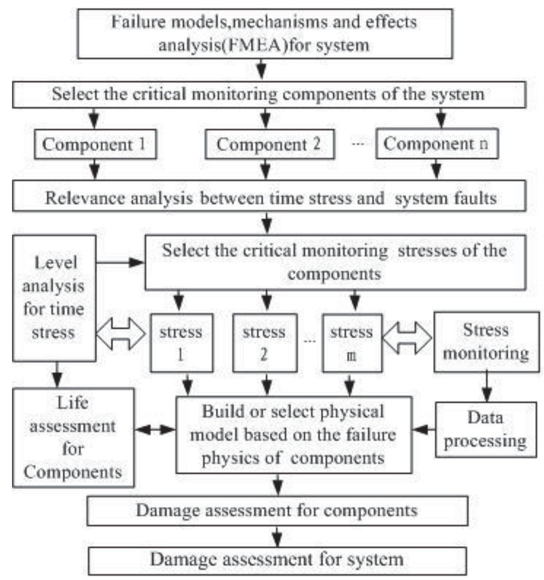

Figure 9. Detail process of DM-LCM technology

b) Synthetical analysis between time stress and system faults

Through the comprehensive analysis of time stress and system fault, the main stress factors causing the failure of gyroscope components can be found out, and the damage degree of the stress at a specific time can be determined. The methods of time stress and system fault comprehensive analysis include neural network, logistic regression, data mining and so on.

c) Level analysis for time stress

It is very necessary to understand and analyse the stress of helicopter gyroscope in the life cycle of manufacturing, operation and transportation. Through the horizontal analysis of time stress of helicopter gyroscope, the variation range of a certain kind of stress (such as temperature) can be found, and the variation range can be divided into several levels for the component life evaluation.

d) Data processing

Most monitoring systems, such as TSMD, are equipped with sensors to measure various stresses in the working environment of the equipment. Sensor as a detection device, it can feel the measured information, and can feel the information, according to a certain rule into electrical signals or other required forms of information output. In the DM-LCM process, we processed the data obtained by the sensor to achieve the data compatibility requirements with the input interface of the selected fault physical model or cumulative damage model.

e) Damage assessment for components and system

In general, damage caused by time stress is considered permanent. The accumulation of total damage induced by the operation at several different stress amplitudes is assumed to be equal to the sum of the damage increments accrued at each individual stress level[8,9].Then we can predict the damage induced by a certain stress level by damage increment under multiple loading conditions.We use the linear damage theory and the Miner cumulative damage theory to describe the model of components damage based on GSPN in this paper. In the series system, the relationship between system damage and component damage is constructed as shown below：

$$D_s(t) = f(D_i(t)) = \max_{i=1,\dots,m} D_i(t) \tag{1}$$

And in the parallel system, it is constructed as shown below:

$$D_s(t) = f(D_i(t)) = \min_{i=1,\dots,m} D_i(t) \tag{2}$$

3) Fault prediction method

It is found that there is a great correlation between the change of stress level and prediction accuracy. However, it is impossible to control prediction accuracy by direct prediction of stress change under current technical conditions. Stress changes can be inferred from historical information such as working conditions and damage conditions. The time series model is usually used for short-term prediction, that is, the statistical sequence has not changed fundamentally in the past. Autoregressive (AR) model is a kind of time series model, which is suitable for short-term prediction of the series with symmetric changes. Aiming at the characteristic that residual life prediction is a typical short-term prediction, we propose a multi-point fault prediction method based on AR mode and LEAP-Frog arithmetic.

The method of fault prediction analyzes based on optimized multi-points damage is shown as Fig10.

a) Analyze of the historical stress degree

Through the analysis of the historical stress degree of the equipment, the basic stress state of the most important stress of the product in the whole life cycle can be determined. The stress degree of the basic stress condition is defined as b.

b) Determination to the order of AR model

The order N of AR model is used to represent the number of historical data used to predict the remaining life, and this parameter can directly affect the prediction trend of the remaining life. The N-order AR model predicting the residual life can be expressed as the following equation

$$\hat{R}_{i,k} = b_k - \sum_{j=1}^{N} a_j R_{i,k-j} \tag{3}$$

where the $\hat{R}_{i,k}$ is the result of prediction, a_j , b_k are the parameter of the model.

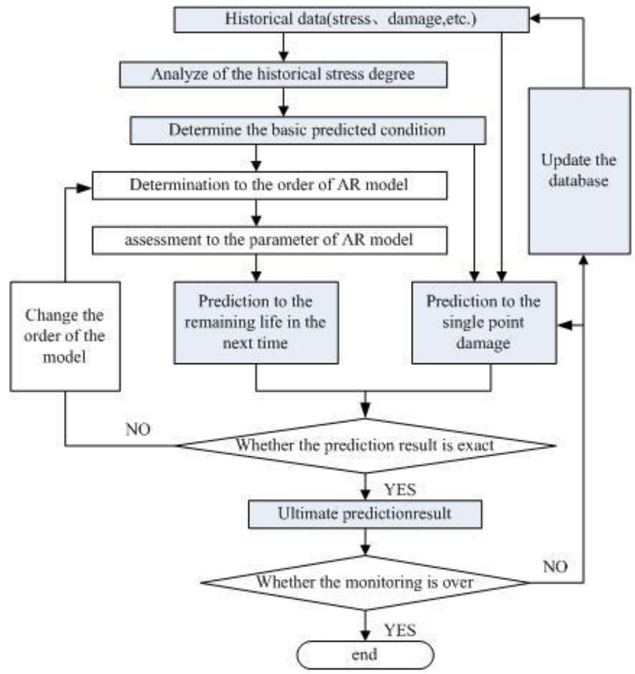

Figure 10. Prognosis process based on optimization AR model

c) The assessment to the parameter of AR model.

There are two main methods for evaluating AR model parameters: direct evaluation and recursive evaluation. The least square method is a common method of direct evaluation, which seeks to evaluate the best parameters of AR model by minimizing the sum of squares of errors in the observation sequence. However, with the growth of data, the so-called "data saturation" phenomenon will occur in the least square method, and the computation amount and computation time will increase greatly. Recursive evaluation can overcome this shortcoming and help to determine model parameters quickly. In this system, recursive evaluation methods based on Burg algorithm and l-d algorithm are adopted for AR model parameter evaluation. The process is as follows:

Firstly, the mean square sum of before and after errors is calculated:

$$\varepsilon = \sum_{k=N}^{M-1} \{[e_{fk}^{(N-1)}]^2 + [e_{bk}^{(N-1)}]^2\} \tag{4}$$

where M is the length of historical remaining life sequence used to prediction. The reflectance can be obtained by the formulation as following:

$$\rho_{\mathrm{N}} = -\frac{2\sum_{k=N}^{M-1} e_{fk}^{(N-1)} e_{bk-1}^{(N-1)}}{\sum_{k=N}^{M-1}[e_{fk}^{(N-1)}]^2 + \sum_{k=N}^{M-1}[e_{bk-1}^{(N-1)}]^2} \tag{5}$$

Then the parameters of AR model are evaluated and the mean square of error is predicted

$$a_N^{(N)} = \rho_N \tag{6}$$

$$a_j^{(N)} = a_j^{(N-1)} + \rho_N a_{N-j}^{(N-1)}, j = 1,2,..., N-1 \tag{7}$$

$$D^{(N)} = (1-\rho_N^2) D^{(N-1)} \tag{8}$$

The prediction error of the next stage is calculated recursively

$$e_{fk}^{(N)} = \hat{R}_{i,k} + \sum_{j=1}^{N} a_j^{(N)} R_{i,k-j} \tag{9}$$

$$e_{bk-1}^{(N)} = \hat{R}_{i,j-N-1} + \sum_{j=1}^{N} a_j^{(N)} R_{i,k-N-1+j} \tag{10}$$

At last, each time the stress is monitored, the cumulative damage changes. After a period of stress monitoring, the cumulative value of damage changes caused by a stress can be obtained, and then the evaluation value can be obtained by the prediction method. Based on the above methods, an advanced recursive prediction model based on single point is constructed to improve the efficiency.

$$R_{i,k} = R_{i,k-1} - \overline{L}_{i,b} * \Delta d_{i,k} \tag{11}$$

where $\overline{L}_{i,b}$ is the average life under the basic stress condition which is ascertained in the step (1), the initialization of recursion is defined as $R_{i,0} = \overline{L}_{i,b}$.

d) Comparison between AR model and single point damage prediction results

The predicted results $\hat{R}_{i,k}$ of AR model were compared with the predicted results of single point damage $R_{i,k}$ by the following formula (12).

$$\Delta R_{i,k} = \left|\hat{R}_{i,k} - R_{i,k}\right| \tag{12}$$

The error $\Delta R_{i,k}$ is less than the threshold λ, indicating that the degradation trend is stable, and the AR model can be used to predict the remaining life. Otherwise, reevaluate the parameters of the AR model until $\Delta R_{i,k} < \lambda$.

e) Update the historical database

When monitoring is incomplete or the component does not fail, the predicted results and the current stress state are added to the history database to update the history database.

E. Health management module

Health management module can be seemed as a bridge between condition monitoring, intermittent fault detection, permanent fault diagnosis, permanent fault prediction and maintenance plan. Intermittent fault detection module can be used to recognize intermittent fault. Permanent fault diagnosis and fault prediction modules can be used to recognize permanent fault. Health management module can be used to assess the amount of damage induced by various stresses and predict when the product might fail. The main functions of this module in our HM system are shown as follow.

1) Manage all the information such as measured data got from BIT and TSMD, diagnosis result, prediction result, equipment information, expert knowledge, etc.

2) Analyze all the information in the databases and make an optimum decision for the helicopters' gyroscope maintenance plan.

The structure of the health management module in our HM system is shown in Fig.11.

In our HM system, in order to analyze the information and make the decision synthetically, the databases reflected the different aspects of the helicopters' gyroscope must be required, and the inference machine is must be provided. Therefore, as shown in Fig.11, the health management module includes several databases: monitoring information database, expert knowledge database, gyroscope's information database and model database. The critical part of health management module is the decision and support system, which implements the analysis and decision process of the HM system.

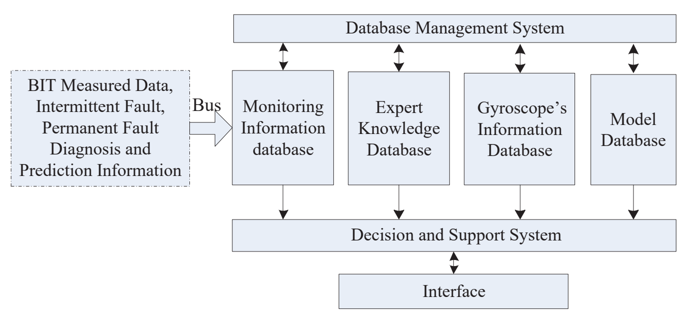

Figure 11. The structure of health management module

V. HM SYSTEM IMPLEMENT

Based on the functions of the above modules, we completed the construction of helicopters' gyroscope health management system. Based on the main BIT system, some TSMD sensors, such as vibration sensor, temperature sensor and test circuit, are added to the hardware of the health management system. The hardware is shown in Fig. 12.

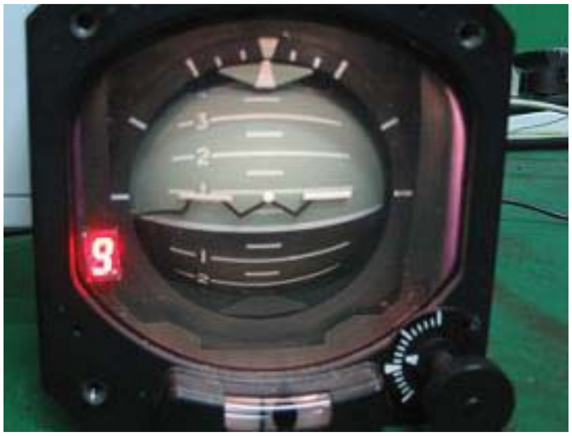

Figure 12. Helicopters' gyroscope HM system indicate interface

We use Delphi and other visual programming language tools to write the external ground software of helicopter gyroscope HM system. Some interfaces of the software are shown in Fig.13~ Fig.14.

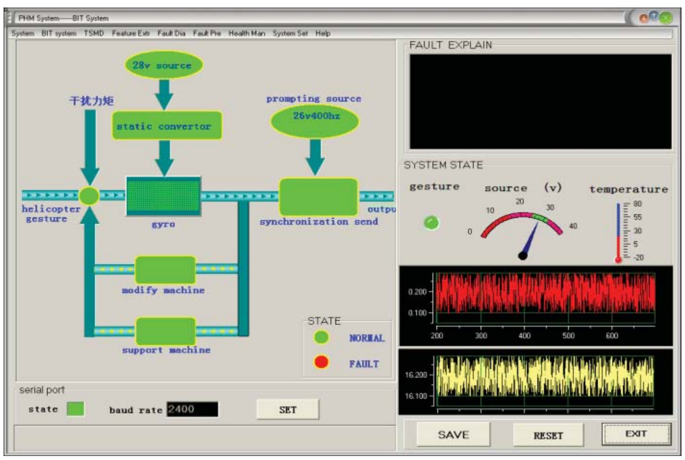

Figure 13. BITsystem interface

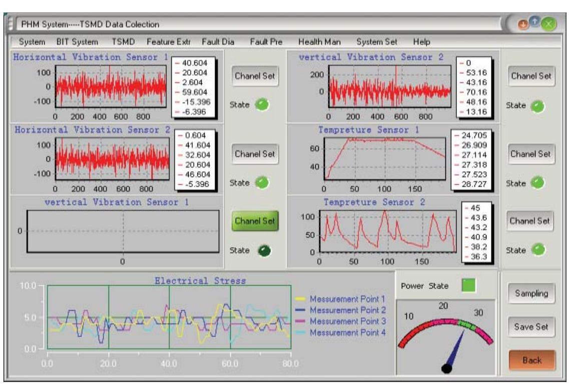

Figure 14. TSMD data collection interface

VI. Conclusion

With the continuous development of health management technology, health management system has gradually become an important part of the realization of automated logistics, and its application in the real world has also received more and more experts and scholar's attention. Based on the intermittent fault characteristics of helicopter gyroscope and the design technology of in-flight test (BIT) system, this paper presents a HM architecture of helicopter gyroscope. This system can improve the capability of fault prediction and false alarm recognition of helicopter gyroscope, and can also be applied to other similar equipment.

Acknowledgment

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