CHEMICAL ENGINEERING TRANSACTIONS

VOL. 33, 2013

A publication of AIDIC
The Italian Association of Chemical Engineering
Online at: www.aidic.it/cet

Guest Editors: Enrico Zio, Piero Baraldi

ISBN 978-88-95608-24-2; **ISSN** 1974-9791

DOI: 10.3303/CET1333042

Demonstration Method for PHM-Oriented Testability Design

Chao Wang, Jing Qiu*, Guan-jun Liu, Shu-ming Yang, Peng Yang

Laboratory of Science and Technology on Integrated Logistics Support, College of Mechatronics and Automation, National University of Defense Technology, Changsha, 410073, China
qiujing16@sina.com

The development of PHM propels the combination of design for testability and relevant PHM technology, which leads a need for the demonstration of PHM-oriented testability design. The paper mainly introduces the evaluation and demonstration method ranging from the design phase to the demonstration phase. Firstly, the index set to be evaluated is established according to the feature of the PHM-oriented testability design and its difference between the traditional testability. Then, an indexes estimation method for the design phase which is based on the testability model is proposed. In this method, a testability design and modeling software TADS is introduced and applied. Thirdly, demonstration test based on physical fault injection is introduced. The test plan covers the sample size determination, sample distribution and fault mode selection from the mode set. Two sample size determination methods based on classical binomial distribution and Bayesian posterior risk criterion are introduced. Finally, an example of flying control system is given to verify the proposed methods.

1. Introduction

With the development of PHM and design for testability (DFT), it is a tendency that combining both technologies to form a PHM-oriented testability, which not only includes the fault detection and isolation, but also provides information support for equipment status monitoring and maintenance measurement. The PHM-oriented testability can be defined as design feature that the equipment can get the status (workable, un-workable or declined), isolate the failure, prognosticate key failures and evaluate the health status. Simon et al. (2009) has focused on the PHM oriented sensor selection and optimization. Zhang et al. (2008) also takes research on the sensor optimization for PHM. Yang et al. (2012) takes research on the equipment health oriented testability design and proposes relevant methods for establishment of indexes set, sensor optimization and test timing optimization.

The demonstration for PHM oriented testability is a process to check that whether the testability indexes of the equipment meet the requirements in the contract. The demonstration covers the life cycle of the equipment and methods vary with the design or operation stages. According to the operation stage, the testability demonstration can be divided into the analysis demonstration, physical test demonstration and operation demonstration. Analysis demonstration is usually applied in the design phase and the testability model is used to get the indexes. For example, testability modeling software TEAMS of QSI and eXpress of DSI have the indexes evaluation function which use the failure-test dependency model in the analysis.

Physical test demonstration is carried out by injecting faults on the physical prototype of the equipment and making statistical analysis on the result. The sample size determination is based on some military standards or classical statistical methods based on binomial and normal distributions, and the sample size is usually large, which brings higher test cost and risks for the complicated equipment. So some test planning methods based on Bayesian small sample theory is studied. Li et al. (2009) proposes a sample size determination method which takes advantage of the testability prior information to decrease the size. In addition, Martz (2008) uses a planning method based on Bayesian posterior risk criteria in the reliability demonstration of the emergency diesel generator.

Please cite this article as: Wang C., Qiu J., Liu G., Yang S.M., Yang P., 2013, Demonstration method for phm-oriented testability design, Chemical Engineering Transactions, 33, 247-252 DOI: 10.3303/CET1333042

2. PHM-oriented testability indexes set

The indexes set of PHM-oriented testability includes two aspects, the indexes to depict the detection/isolation capacity and the indexes to depict the prognostics capacity. So besides the indexes in traditional testability which include the fault detection rate (FDR), fault isolation rate (FIR), false alarm rate (FAR), fault detection time (FDT) and fault isolation time (FIT), two new indexes are proposed to evaluate the capacity on fault prognostics.

Fault prediction rate (FPR), which means the ratio of the predicted failure modes to the total failure modes need to be predicted with the given prognostic model and algorithm during certain period. Its definition equation is as follow.

$$FPR = N_{CP} / N_{RP} \tag{1}$$

While N_{CP} is the correctly predicted failure mode number, N_{RP} is the total failure mode number to be predicted in testability design. The prognostics capacity is closely relevant with the testability model and prognostic algorithms, which include the data-driven prognostics, the model based prognostics and the knowledge based prognostics. Sometimes, the three methods are combined in prediction.

Fault prediction time (FPT), which means the prediction time with the given model and method under certain prediction accuracy.

The fault intensity and the degradation process need to be considered in determining the value of the FPT. In the primary operation of the equipment, the fault characteristic is not significant, the prediction accuracy is low and the FPT is longer. With the evolution of fault, the prediction accuracy increases. If the prediction time is not long, some faults will incur in the time span and cause accident. The fault prediction time also takes influence to the maintenance and availability. So the maintenance scheme and fault status should be considered in determining the FPT.

In the indexes set of PHM-oriented testability, FDT, FIT and FPT are the requirement on time effectiveness, while FDR, FIR and FPR reflect the requirement on capacity of fault detection, isolation and prediction respectively.

3. Analysis demonstration

Analysis demonstration is a process which uses the testability model to evaluate the testability design. The basis of the analysis demonstration is the elaborate testability design and accurate component data, which include the system function and structure, the FMECA result, fault rate data, the selection of test point. The output of the analysis includes FDR, FIR, FPR, un-detected or un-isolated component, testability advice and so on.

As an important section in testability demonstration, the analysis demonstration in the design phase is the first assurance for a good testability level. It can give both qualitative and quantitative analysis of the model, which can be used as guides for modifying the testability design. The testability design is an iterative process of analysis and modification. The flow is shown in Figure 1.

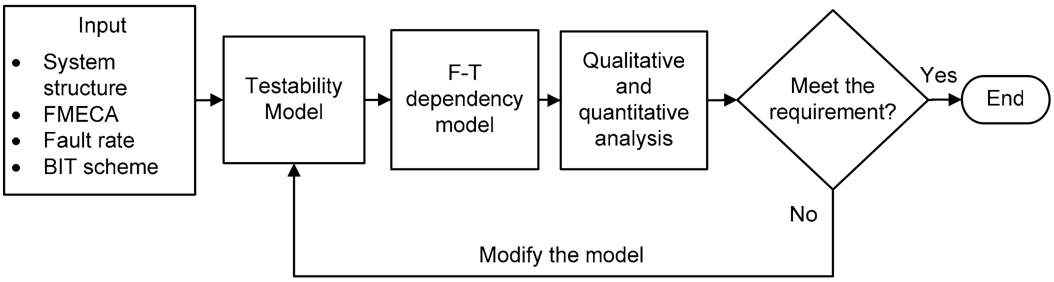

Figure 1: Iterative process of analysis and modification in testability design

Analysis demonstration is carried out after obtaining the fault-test (F-T) dependency matrix, which is established from the testability model. While obtaining the F-T dependency matrix, we can get the detectable mode set F_D, the isolable mode set F_D and predictable mode set F_P. The prediction value of FDR, FIR and FPR can be defined as follow.

$$\begin{cases} FDR = \sum_{f_i \in F_D} \lambda_i \Big/ \sum_{f_i \in F} \lambda_i \\ FIR = \sum_{f_i \in F_I} \lambda_i \Big/ \sum_{f_i \in F_D} \lambda_i \\ FPR = \sum_{f_i \in F_P} \lambda_i \Big/ \sum_{f_i \in F_{RP}} \lambda_i \end{cases} \tag{2}$$

Where F denotes all the failure mode set of the system testability model, λ_i is the failure ratio of the mode *i* and is the detectable mode set, F_D is the isolable mode set, F_P is the predictable mode set and F_{RP} is the mode set need to be predicted.

4. Physical test demonstration

The physical test demonstration is implemented by injecting faults into the testability prototype of the equipment artificially. The overall test includes the determination of sample size, sample size distribution, fault mode selection, fault injection and the final judgment. The demonstration flow is shown in Figure 2.

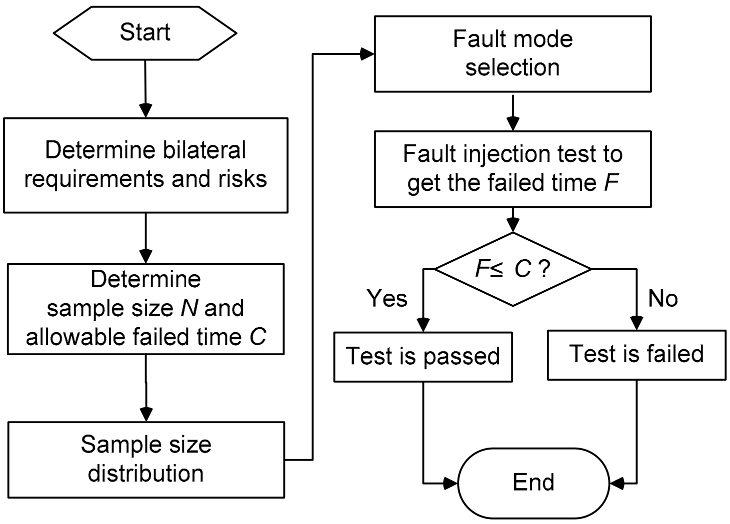

Figure 2: Flow chart of the physical test demonstration

4.1 Sample size determination

As the test result of the failure injection is a success or failed detection/isolation/prediction, so the sample size determination method is based on a binomial distribution.

For the indexes such as FDR, FIR and FPR, in a success-failure test, there are two specified values for the testability level: π_0 , the producer testability level (PTL), which is the up level to ensure the product to pass the test with a higher chance; π_1 , the consumer testability level (CTL), which is the level set by the consumer to reject the test when the testability level is lower than the CTL. There are usually two risk criteria in the test plan. The producer's risk α , the probability of failing the test when the testability level is π_0 . The consumer's risk β , the probability of passing the test when the testability level is π_1 . For a test scheme (N, C) , it satisfies

$$\begin{cases} P(y > C \mid \pi_0) = 1 - \sum_{y=0}^{C} C_N^y (1-\pi_0)^y \pi_0^{N-y} \le \alpha \\ P(y < C \mid \pi_1) = \sum_{y=0}^{C} C_N^y (1-\pi_1)^y \pi_1^{N-y} \le \beta \end{cases} \tag{3}$$

Where N is the total fault number to be injected and C is the maximum allowed number of failed detection, isolation or prediction.

However, in the practical application, the sample size of the classical binomial method is relatively large. The sample size determination method based on Bayesian theory can take advantage of the index prior distribution to get a smaller sample size. The prior distribution can be acquired by the test information such as growth test data, expertise information and so on. Assuming that the index prior distribution is $p(\pi)$, under the Bayesian posterior risk criteria by Hamada et al. (2008), the posterior risks are as below.

The posterior producer's risk (PPR) is

$$PPR = P(\pi > \pi_0 \mid Test\ is\ Failed) = \int_{\pi_0}^{1} p(\pi > \pi_0 \mid y > C) d\pi$$
$$= \int_{\pi_0}^{1} \frac{f(y > C \mid \pi) p(\pi)}{\int_0^1 f(y > C \mid \pi) p(\pi) d\pi} d\pi = \frac{\int_{\pi_0}^{1} [1 - \sum_{y=0}^{C} C_N^y (1-\pi)^y \pi^{N-y}] p(\pi) d\pi}{1 - \int_0^1 [\sum_{y=0}^{C} C_N^y (1-\pi)^y \pi^{N-y}] p(\pi) d\pi} \le \alpha \tag{4}$$

The posterior consumer's risk (PCR) is

$$PCR = P(\pi < \pi_1 \mid Test\ is\ Passed) = \int_0^{\pi_1} p(\pi \mid y \le C) d\pi$$
$$= \int_0^{\pi_1} \frac{f(y \le C \mid \pi) p(\pi)}{\int_0^1 f(y \le C \mid \pi) p(\pi) d\pi} d\pi = \frac{\int_0^{\pi_1} [\sum_{y=0}^{C} C_N^y (1-\pi)^y \pi^{N-y}] p(\pi) d\pi}{\int_0^1 [\sum_{y=0}^{C} C_N^y (1-\pi)^y \pi^{N-y}] p(\pi) d\pi} \le \beta \tag{5}$$

To get the test scheme, simultaneously solve the inequalities given by

$$PPR = P(\pi > \pi_0 \mid Test\ is\ Failed) \le \alpha \tag{6}$$

and

$$PCR = P(\pi < \pi_1 \mid Test\ is\ Passed) \le \beta \tag{7}$$

4.2 Sample distribution and fault mode selection

After determining the sample size, we need to allocate the samples into each component and carry out the fault mode selection to get the fault mode set for injecting.

For some complex equipment, the faults modes amount is usually larger than the calculated sample size and the fault modes to be injected should be representative. The hierarchical distribution method based on fault rate is commonly used in the samples distribution. The relative fault occurring frequency, which combines the number of unit under test (UUT) in current level, the fault rate and working time factor, is used in the method. Firstly, based on the equipment complexity and reliability data, the structure and fault rate data are analyzed. Then, the relative fault occurring frequency of each component is calculated and sample is allocated hierarchically. The fault rate based hierarchical method is a typical probability sampling method, of which the result can mostly reflect the actual fault distribution of the UUT. The distribution is carried out as following.

$$\begin{cases} N_i = NC_{pi} \\ C_{pi} = \dfrac{Q_i \lambda_i T_i}{\sum_{i=1}^{m} Q_i \lambda_i T_i} \end{cases} \tag{8}$$

Where N_i is the sample size allocated to the component i, Q_i is the component amount in current level, λ_i is the fault rate of component i in current level, T_i is the working time factor of component i. m is the component types of the component in current level.

The source of fault mode selection is the result of FMECA. The selection follows a random sampling rule, which selects the distributed sums of fault in corresponding component fault set.

5. Example

A flying control system is taken as an example and the structure chart is shown in Figure 3.

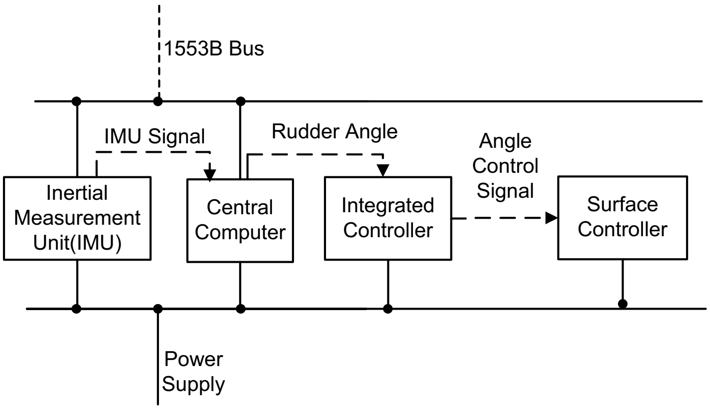

Figure 3: Structure of flying control system

The control system is comprised of power supply, 1553B bus, inertial measurement unit (IMU), central computer, integrated controller and surface controller. The testability of the control system is implemented from the design phase, the testability analysis and design system (TADS) is used to establish the testability model. The model is shown in Figure 4.

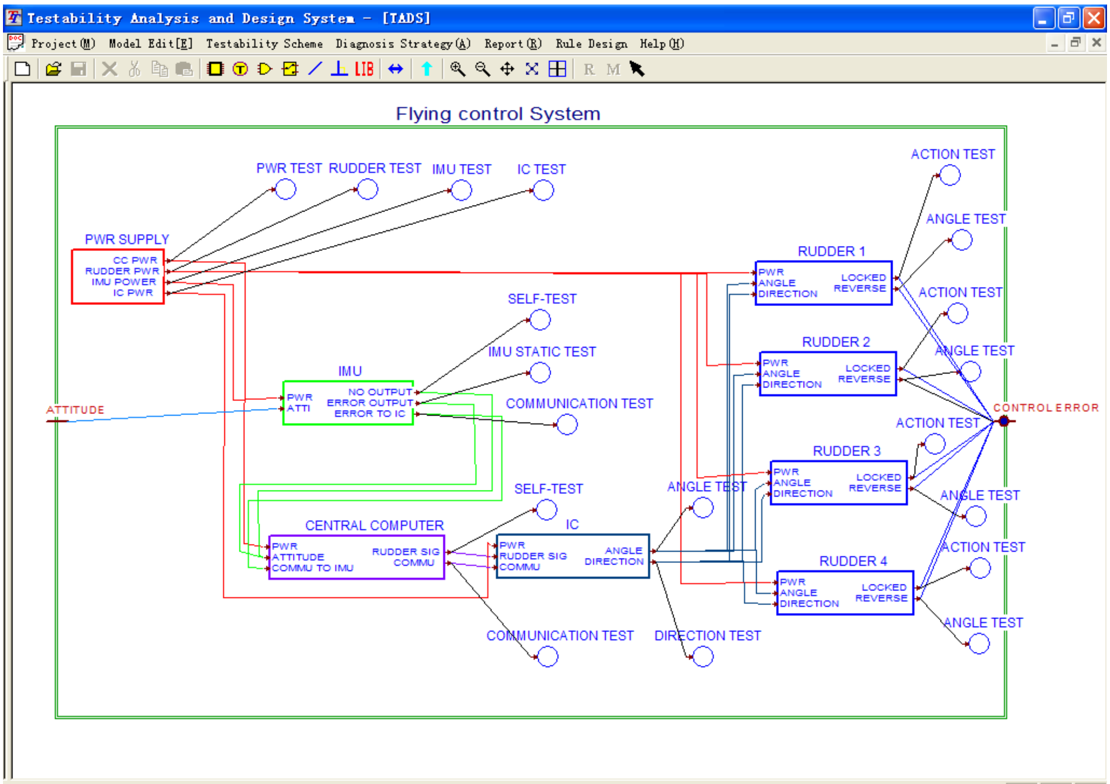

Figure 4: Testability model of flying control system with TADS

The designed indexes are set as FDR=0.95, FIR=0.90, FPR=0.85. An index prediction is made according to the model and the evaluated indexes are FDR=1.00, FIR=1.00, FPR=0.90.

In physical test demonstration test, taking FDR as an example, the bilateral levels and risks are set as: π_0 =0.95, π_1 =0.90, α =0.1, β =0.1. According to the prior test data, the prior distribution of FDR is

$$\pi(p)=\frac{\Gamma(60.2+4.6)}{\Gamma(60.2)\Gamma(4.6)}p^{60.2-1}(1-p)^{4.6-1} \tag{9}$$

With the classical binomial method in equation 3, the test sample size is 187 with a maximum allowable failed detection time 13, while taking advantage of the prior distribution, the test sample size under Bayesian posterior risk criteria is 24 with a maximum allowable failed detection time 2, the sample size is about 13% of the classical scheme.

Here we use the optimal test scheme in physical test. The information for sample distribution including the fault rate, component amount and working time factor are shown in Table 1.

Table 1: Distribution information and result

LRU	Fault rate ($10^{-5)}$	Component amount	Working time factor	Result
Power supply	4.03	1	1	2
1553B bus	5.50	1	1	3
Central computer	5.06	1	1	3
IMU	8.01	1	1	5
Surface controller	3.03	4	1	8
Integrated controller	5.02	1	1	3

Taking the data to equation 8, the sample size distribution result is listed in the last column of Table 1. The component amount of surface controller is 4 and the distributed quota is 8, which means 2 faults to be selected for each surface controller.

The selection of fault mode follows a fault rate based random sampling in the mode set of each LRU, and it will not be illustrated here.

The selected 24 fault modes are injected into the physical prototype of the flying control system, of which 23 faults are successfully detected and only one fault is failed to detect. The failed time is 1 and it is smaller than the allowable failed time 2, so the FDR demonstration test is passed. As the physical test demonstration process of FDR, the demonstration of FIR and FPR can follow the same way.

6. Discussion

The demonstration of PHM-oriented testability is important in assuring the designed capacity. The proposed indexes set and demonstration methods are useful in guiding the demonstration test. However, the proposed methods mainly follow the traditional testability demonstration and the PHM-oriented testability emphasizes the fault prognostics and state evaluation. So it is necessary to study the test methodology under the new restrictions.

References

DSI international (eXpress) <www.dsiintl/WebLogic/products.aspx> accessed 12.12.2012

Hamada M.S., Wilson A.G., Reese C.S., Martz H.F., 2008, Bayesian Reliability. Springer, New York, U.S.A

Li T.M., Qiu J., Liu G.J., 2009, New methodology for determining testability integrated test scheme with test data in the development stages, Journal of Mechanical Engineering, 45(8), 52-57 (in Chinese).

QSI (TEAMS) <www.teamqsi.com/TEAMS.html> accessed 12.12.2012

Simon D.L., Garg S., 2009, A systematic approach to sensor selection for aircraft engine health estimation, NASA/TM-215839.

Yang S.M., Qiu J., Liu G.J., 2012, Sensor optimization selection model based on testability constraint, Chinese Journal of Aeronautics, 25(2):262-268.

Zhang L., Zhang F.M., 2008, Research on optimal sensor placement in equipment health management, Transducer and Microsystem Technologies, 27(7), 18-20 (in Chinese).