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The Preliminary Study of Reliability of AMB System with FTA Method

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Abstract: Because of a lot of advantages, Active Magnetic Bearing (AMB) is widely applied in many fields especially for high-speed rotary machines. The reliability of the system is one of the most important indicators to measure AMB's performance. With the way of Fault Tree Analysis, the potential probability of the whole system broken down can be calculated, which could provide some theory basis for the designer.

Keywords: AMB, FTA, Reliability

I. Introduction

Active Magnetic Bearing (AMB), known as its advantages over the conventional bearings, such as contact-free, no-lubricating and active damping vibration, is widely applied to a lot of fields. AMB, a complicated and multi-disciplinary system, which consists of mechanical and electrical parts, including stator bearings, rotor, auxiliary bearings, sensors, controller and power amplifiers etc. could breakdown when any part has a problem. In order to avoid appearing this horrible accidence, especially in some special situation such as high-speed rotary machines, nuclear equipments and space flights etc. reliability analysis is necessary for the AMB system to improve the safety and stability. So this paper focuses on the reliability of the AMB system with the Fault Tree Analysis (FTA), which could provide the theory basis for the engineering.

Fault Tree Analysis (FTA) is an effective method, which finds out the cause of failure with the way from top to down refining the trouble. FTA takes the serious failure as the analyzing goal at first, next finds out all the direct reasons causing the failure, and then discoveries all the elements causing these direct reasons. With step by step tracing, the original event with the certain failure reason or probability distribution is the basic result of analysis. So FTA is a tool of reliability for some complicated dynamic system、factory test and work field failure etc. The propose of the FTA is to judge the basic failure, and find out the reason、influence and the probability.[1,2]

II. Design principle

Usually, FTA defines the serious failure as top event, the original event as basic event. The Table of Fault Tree could show not only the relation of cause and result, but also the logic of system with the top event, basic events, middle events and some logic gates.

Fig.1 shows the operation principle of AMB. The serious trouble of this system is the rotor couldn't suspend. So take the rotor inactivation as the top event of the failure analysis, define the fault of primitive unit as basic event (such as sensor unit, power amplifier unit， stator bearing coils .etc), the middle parts as middle event (such as controller).

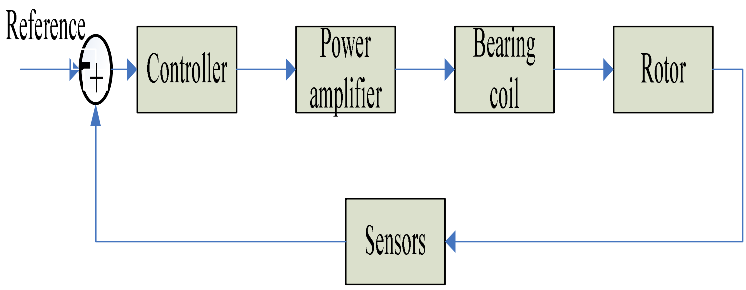

Fig 1: the AMB's principle of operation

From the Fig.1, AMB realizes the system's function by connecting all the parts in series. In this kind of connecting, any part's trouble could let to the breakdown of the whole system. Because of its complication, taking two- degree of freedom AMB system for example, there are two displacement sensors, four bearing coils, four power amplifiers, one controller and other parts in whole. Fig.2 (the fault tree of AMB) and Table 1(the table of fault tree) are both based on the definition above.

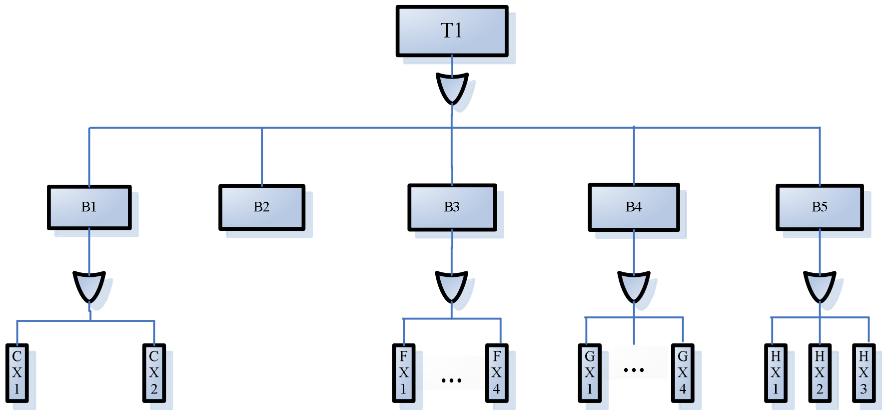

Fig 2: the fault tree of AMB

Table 1: the table of fault tree

NO	Signification	Kind of event
T1	Inactivation of rotor	Top event
B1	Fault of sensors	Middle event
B2	Fault of controller	Middle event
B3	Fault of power amplifiers	Middle event
B4	Fault of Bearing coils	Middle event
B5	Fault of others	Middle event
CX1	Fault of No.1 sensor	Basic event
CXn	Fault of No.2 sensor	Basic event
FX1	Fault of No.1 modular of amplifier	Basic event

FXm	Fault of No.4 modular of amplifier	Basic event
GX1	Fault of No.1 bearings	Basic event
GXm	Fault of No.4 bearings	Basic event
HX1	Fault of power supply	Basic event
HX2	Fault of cable	Basic event
HX3	Fault of interface	Basic event

According to the fault tree (Fig.2), every kind of possibility of failure situation is listed, and so the relationship between top event and basic events can be shown in the Eq.(2.1). The total failure rate of the system should be calculated by (2.1).

$$T_1 = B_1 + B_2 + B_3 + B_4 + B_5 = CX_1 + CX_2 + BX_2 + FX_1 + FX_2 + FX_3 + FX_4 + GX_1 + GX_2 + GX_3 + GX_4 + HX_1 + HX_2 + HX_3 \quad (2.1)$$

From the Fig.2, all of the basic events are independent, so all of these events(including [CX_1]、[CX_2]、[BX]、 [FX_1]、[FX_2]、[FX_3]、[FX_4]、[GX_1]、[GX_2]、[GX_3]、[GX_4]、[HX_1]、[HX_2]、[HX_3].) can be defined as the minimal cut-set(MCS), which means any one of them with trouble could cause the AMB system collapse.

Failure rate p presents the rate of system fault at the instant time, and some names it the "risk rate", which is the one of the standard to judge the system's reliability. In the theory of the reliability mathematics, the failure rate is a kind of conditional probability. In order to easy to analyze, assure the failure rate of [HX_1]、[HX_2]、[HX_3] is zero. Based on the theory of FTA, the probability of affair T_1 happening can be computed by the structure function expressing by the minimal cut-set.

$$g = \sum_{j=1}^{k}(-1)^{(j-1)} F_j = \sum_{r=1}^{k} P_r\{E_r\} - \sum_{1<i<j<k} P_r\{E_i \cap E_j\} + \ldots + (-1)^{(k-1)} P_r\{\bigcap_{r=1}^{k} E_r\} \quad (2.2)$$

In Eq.(2.2),

k: the number of the minimal cut-set;

E_r : the failure rate of the minimal cut-set;

F_1: the failure rate of only one minimal cut-sets happening one time, which can to calculate the quantitative valuation of fault tree;

F_2 : the failure rate of two of the minimal cut-sets happening one time;

F_k : all of the minimal cut-sets happening at same time. Back to the AMB system,

Assuming the failure rate of basic event X_i is P_i, hence $P(X_i)=p_i$. The failure rate of every basic event under the same middle event is equal, so

$$p(CX_i) = p_c, p(FX_i) = p_f, \quad p(GX_i) = p_g, i = 1,2,\ldots,4; \quad (2.3)$$

Because of serial connecting, all of the minimal cut-sets are independent, F_1, F_2

$$F_1 = E_1 \cup E_2 \ldots \cup E_k = 1-(1-p_b)(1-p_c)(1-p_c)\ldots(1-p_g) = 1-(1-p_b)(1-p_c)^2(1-p_f)^4(1-p_g)^4 \quad (2.4)$$

$$F_2 = \sum_{1<i<j<k} P\{E_i \cap E_j\} = 2P\{B_x \cap C_x\} + 4P\{B_x \cap F_x\} + ... + 6P\{G_x \cap G_x\} = 2p_b p_c + 4p_b p_f + 4p_b p_g$$
$$+ p_c^{\ 2} + 8p_c p_f + 8p_c p_g + 6p_f^{\ 2} + 16p_f p_g + 6p_g^{\ 2} \tag{2.5}$$

In same way, all of F_3, F_4, ... F_{11}, could be listed. But from the equations above, the calculation is very complicated because of 11 minimal cut-sets in this example except using special software. In order to find out the most important influence for the failure tree, some defaults are given coming from the experience:

If every minimal cut-set' failure rate is smaller than 0.1, all of those events should be taken as independent, and the final TI could calculated by Eq.(2.6):

$$T_1 \approx E_1 \cup E_2 ... \cup E_k = 1 - (1-p_b)(1-p_c)^2(1-p_f)^4(1-p_g)^4 \tag{2.6}$$

If every minimal cut-set' failure rate is smaller than 0.01, all of those events should be taken as independent, and the final TI could calculated by Eq.(2.7):

$$T_1 \approx E_1 \cup E_2 ... \cup E_k = p_b + 2p_c + 4p_f + 4p_g \tag{2.7}$$

III. RESULT

In order to understand smoothly, the sensors, the power amplifiers and the bearing coils are taken as the basic events in the fault trees from the Fig.2. Actually all of them are very complicated components, composed by a lot of electrical and mechanical devices. For instance, sensor is made up by probe and demodulation circuit, and both of them are built up by a lot of chips, connected by all kinds of wire and mechanical parts. So the failure rates of those basic events (sensors, amplifiers, bearing coils) are hard to be got.

Because there are no exact failure data and related standards about AMB system, a longtime running (at least 10years) should be done to obtain the first-hand data. Thinking about the limitation, the failure rate is estimated below which based on some experiments (the total operating time of a set of AMB system is over 3000 hours) and some documentations[3]:

Table 2: the table of the basic event's failure rate

NO	Failure rate
Pb	0.1×10^{-3}
Pc	0.2×10^{-3}
Pf	0.3×10^{-3}
Pg	0.3×10^{-3}

Putting the data into the Eq.(2.7), then the result is:

$$T_1 = 2.9 \times 10^{-3} \tag{2.8}$$

IV. CONCLUSION

This article is preliminary to introduce how to analyze and calculate the failure rate of AMB system with FTA and the work has just started. Follow-up work should continue:

1. Compute some other important index of reliability (e.g. structure importance);
2. Program the software to solve the complicated operation of T_1;
3. Specify every basic event' fault tree to get appropriable failure date;
4. Combine FTA with FMECA (Failure Mode, Effects and Criticality Analysis) to improve the system's safety.

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