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Dynamic Analysis of Catapult Availability Based on CBM

Xia Guo-Qing, Luan Tian-Tian, Sun Ming-Xiao and Liu Yan-Wen

College of Automation, Harbin Engineering University, Harbin 150001, China
luantiantian1988@126.com

Abstract

The repair of catapult is a complicated engineering. In this paper, the method of Condition Based Maintenance is applied into the repair system based on the catapult maintenance of system analysis. In view of the application of Condition Based Maintenance in the modern aviation equipment, the catapult availability is the final goal. The structure of catapult maintenance system is analyzed. The structure model of system dynamic feedback is established by using system dynamics method. Simulation is based on the "Nimitz" actual data of the Surge operation in 1997. The results prove the effectiveness and rationality of the proposed method. Through the analysis of the simulation evaluation results, the method applying Condition Based Maintenance into catapult repair system can improve catapult availability.

Keywords*: Catapult; Condition Based Maintenance; System Dynamics; Repair System*

1. Introduction

In the study of aviation maintenance, Condition based Maintenance (CBM) is a maintenance mode. It is combined with engineering practice closely. The main characteristic of this maintenance mode are the premise of accurately grasping actual technical condition of equipment, the principle of less disassembly, less dismantlement and less repair, the goal of maximum extension work time and improve the economic benefit.

How to reveal objective laws of catapult maintenance system process with CBM from the perspective of the researches on the dynamic mechanism, and to support the catapult availability is one of the theoretical frontier in the field of military service. Today, it is mostly based on the theory of probability and mathematical statistics method about CBM state model and decision method [1-3]. This traditional modeling method is based on the component or subsystem structure relations and the reliability characteristics to establish optimization model or statistical model. Many deficiencies are exposed in practice. Firstly, the assumptions have strict requirements. The models often ignore the maintenance time and maintenance resource constraints. It is limited applied to the catapult complex equipment maintenance issues. Secondly, the catapult availability system is the complex feedback and delay [4-5]. It cannot deeply consider the correlation between the internal factors of the system and the conditionality of external factors. It is lack of macro control ability. Therefore, the effect of the model and the nature of the system are difficult to observe and judge. Then, from the angle of maintenance [6-8], people pay more attention to the change of the whole system. The traditional models are often limited to the details. They ignore the factors of the actual catapult availability in the operation of the system's influence. The maintenance system based on CBM is a complex dynamic system. The existing research methods of complex aviation equipment maintenance problems mainly focus on the analysis and processing of the system external data. The considerations of the influence factors of internal system maintenance process and the change characteristics of the various factors are less. It is hard to reveal the essence of the law deeply. So it is difficult to reflect the rate of maintenance activities

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flexibly. It gradually cannot satisfy the requirement of modern military analysis. In conclusion, it is an urgent need to start from a new angle to make exploration and analysis of the maintenance system.

System dynamics (SD) method is good at describing and analyzing system of flow velocity and accumulation [9-10]. It is suitable for the study of logistics interactive dynamic system. SD method provides a top-down and strategic level description method. The method is qualitative and quantitative analysis, systems thinking, systems analysis, synthesis and reasoning [11-14]. It emphasizes the system view, and contact, development and movement view. It has more superiority than traditional operational research method in the research of highly nonlinear, high order, multivariable and multiple feedbacks, complex time-varying large-scale system problems [14-17].

Therefore, in order to get good quantitative description of dynamic, complex and multiple feedback characters of a complex aviation equipment maintenance system under limited resource constraints, this paper takes changes of catapult availability system as a complex behavior caused by internal feedback in the system. The mutual feedbacks between different components in the system are explored by means of system dynamics.

2. Analysis of Catapult State

According to the basic principle of maintenance theory, CBM is a way of preventive maintenance in aviation maintenance activities. It is based on the specific equipment, specific system and specific part of catapult.

The process from catapult degradation to breakdown is a process from gradually function and status degradation during the service period constantly under the influence of all kinds of work stress and environmental stress to eventually breakdown in essence.

Performance degradation means that the equipments are damaged. If the situation continues, it will inevitably produce functional failure. Figure 1 depicts the catapult degradation process.

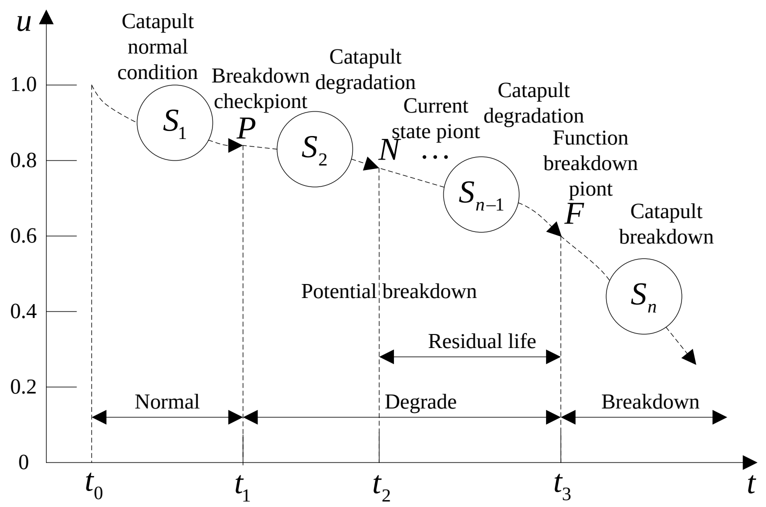

Figure 1. Catapult Degradation Process

In the Figure 1, the X-axis is time t and Y-axis is health index H. The domain of health index is $[0,1]$. When there is no failure in health, health index is 1. When device performance degrades, health index is between 0 and 1. Health index is 0 when the equipment breakdowns.

System statuses are denoted with a limited set of positive integers: state space $S = \{1, 2, \ldots, n\}$, S_1 is the system in good condition, $S_2 \sim S_{n-1}$ is the system state of degradation, S_n is the system state of breakdown. Process of degradation state $\{S(\mathrm{t}) = 1, 2, \ldots, \mathrm{n}\}$ is uniform discrete time Markov chain. When $t = 0$, the system state is S_1. Without considering the maintenance, equipment performance degradation process is not reversible. Each state can shift to the right side state. Each state can also transfer to itself at the same time.

As shown in Figure 1, the process of the catapult performance degradation is divided into three stages: normal, degrade and breakdown.

1) Normal state.

Normal state refers that the key components of a catapult have its normal work performance. In Figure 1, at the beginning period time of the catapult, as there is no breakdown, all of its performance parameters must fluctuate within the acceptable range of S_1. The spare parts are in good condition. As the growth of the working time, its damage is cumulative. It leads catapult health index H to a downward trend.

2) Degrade state.

When a catapult comes to breakdown checkpoint P, as a result of the action of work stress and environmental stress, it makes the health index gradually declines and the performance parameters begin to degrade slowly. During this period of time, key components of a catapult can partially complete the normal functions. But there is a big deviation from normal. The deviation reflects the degree of performance degradation. As the potential breakdown of key components caused by the abnormal working behavior will be detected. Until the system comes to function breakdown point F, during this time a catapult condition is characterized by equipment performance degradation of abnormal behavior. The average life is the period of time from the current state point N to the function breakdown point F. The main task of CBM is to detect early potential breakdown state of key components between point P and point F. According to the current health status of spare parts and usage of loads, equipment average life is forecast. It is to avoid breakdown and to find a suitable point to implement the corresponding maintenance activities before breakdown.

3) Breakdown state.

Catapult function breakdown refers that the breakdown of key components cause the whole part cannot perform its normal functions. From the view of catapult health, when the health index is lower than a certain value, the equipment comes into breakdown state. It belongs to breakdown state within this range, though the healthy index is not 0. The function breakdown of a catapult may be caused by a component breakdown, while the other key components of a catapult may still work normally.

When the device performance parameters meet the breakdown interval S_n, catapult has been unable to meet the corresponding functional requirement. The breakdown causes of a catapult have to be diagnosed. And the maintenance is implemented.

Generally speaking, good economic benefits can be obtained to choose the reasonable maintenance mode. In order to prevent the breakdown of a catapult during use, preventive maintenance must be typically implemented after a period of time. Preventive maintenance has two ways of Time based Maintenance (TBM) and CBM. The cycle of TBM is determined according to the statistics. The management is easy to operate. But sometimes it will influence the execution of the tasks. It may cause excessive or insufficient maintenance. In some occasions, the maintenance of normal catapult will reduce the equipment reliability and increase breakdown rate. The Best Maintenance Time is determined according to the actual status. The idea is based on the analysis of fault mechanism. According to the result of undisassembling test, it is to find a suitable point to implement the corresponding preventive measures to adjust, repair or replacement after a catapult comes into degradation state. It can avoid function breakdown. It makes the maintenance more targeted. It is effective in preventing the breakdown and making full use of the catapult life. Therefore, in the process of shifting from TBM to CBM, it will make maintenance system more targeted with the application of CBM.

3. Catapult Availability System Description of SD

As the catapult availability system based on CBM is a complex nonlinear system. This paper studies a number of similar catapult complex maintenance system. General computer simulation method is hard to describe the complex relationship of related factors. It must proceed from the overall system to research and analyze this system. The dynamic changes of system can be researched from interdependence and mutual restriction relations between the whole and the parts. System dynamics simulation method can clearly express the relationship between system elements. It can effectively to simulate and analyze the characteristics of the dynamic behavior in such complex maintenance system.

3.1. Cause-and-Effect Relation Chart

Through analyzing the feedback relations of the relevant factors in the aviation equipment maintenance system, in the catapult availability system based on CBM, the states can be divided into available condition, degraded condition and broken-down condition according to the degrees of degradation. The maintenance way has changed from traditional preventive maintenance (TBM) to preventive maintenance (CBM) for the catapult. Breakdown Maintenance (BM) is implemented in the broken-down condition. For the catapult in the degraded condition, the former is to keep its status and the latter is to restore the status. The SD cause-and-effect chart is establish and shown in Figure 2.

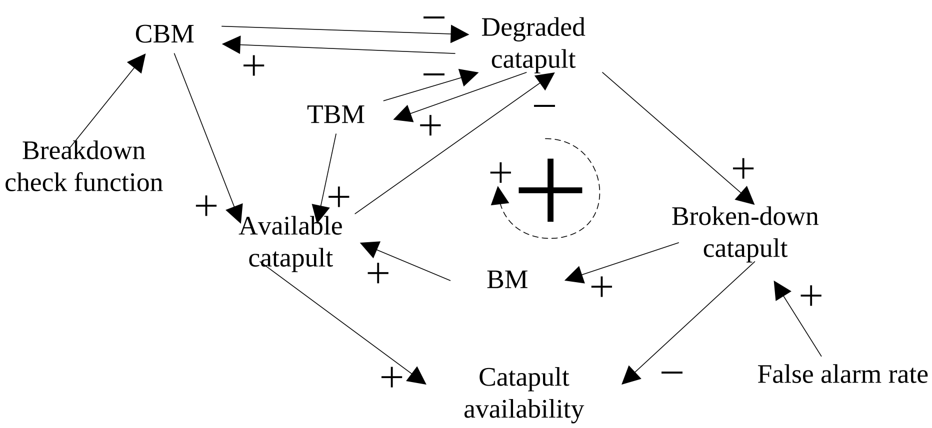

Figure 2. Cause and Effect Feedback Chart

Figure 2 is a feedback loop. The mechanism is based on the process of the gap gradually approaching zero. The available catapult, degraded catapult and broken-down catapult constantly tend to expect purpose under the function of CBM, TBM and BM. In the initial state, the catapult is in good condition. This is the available catapult in the feedback loop. With time gone and use of a catapult, it becomes degraded catapult. And CBM is joined in the feedback loop to preventive maintenance the catapult detected the potential breakdown timely. Obviously, although there is CBM, the abilities of condition monitoring and fault diagnosis are limited, it is hard to avoid that the degraded catapult is not detected. Considering that the situation will cause harm to the catapult. Thus the traditional TBM is adopted in the feedback loop in order to avoid that the degraded catapult is not detected. BM is implemented in breakdown condition. Therefore, the available catapult will increase with CBM, TBM and BM. Under certain conditions of the catapult maintenance system, the increase of available catapult will increase catapult availability.

The assumptions of problem include:

(1) There are 3 states: available catapult, degraded catapult and broken-down catapult.

(2) There are BM, TBM and CBM in the system. TBM is an auxiliary of CBM.

(3) CBM, TBM and BM are completely maintenances.

(4) Detection work does not disturb the operation of equipment.

(5) Sudden accidental breakdown is not considered.

(6) The human resource constraints and maintenance management system constraints are not considered.

3.2. Relationship Flow Diagram

The structure of the flow diagram can reflect the structure of a system more clearly than figure than cause and effect feedback chart. The flow diagram of catapult availability system based on CBM is established according to convergence loop of cause and effect feedback chart. It can be quantitatively expressed more clearly the relations between the variables in the system. It is shown in Figure 3.

In order to quantitative relationship between system variables, it is explained by the actual process to show dynamic cognitive process of the catapult availability system based on CBM.

The flow diagram of SD in Figure 3 shows the quantitative expression of cause and effect relationship in Figure 2. It not only more clearly expresses logistics and feedback control structure, but also defines the quantitative relationship between the variables by mathematical equations.

Figure 3 fully analyzes each state variable and rate variable of the catapult maintenance process. Flow diagram model of the catapult maintenance is build. The box denotes accumulated state variables, such as available catapult, degraded catapult, broken-down catapult, *etc*. Double line connecting to the state variables denotes the increase or decrease behavior of state variables. It is measured by inflow rate and outflow rate, such as the degraded rate, BM execution rate and CBM start-up rate, *etc*. The arc with fine arrow denotes the quantitative and logical relation between variables.

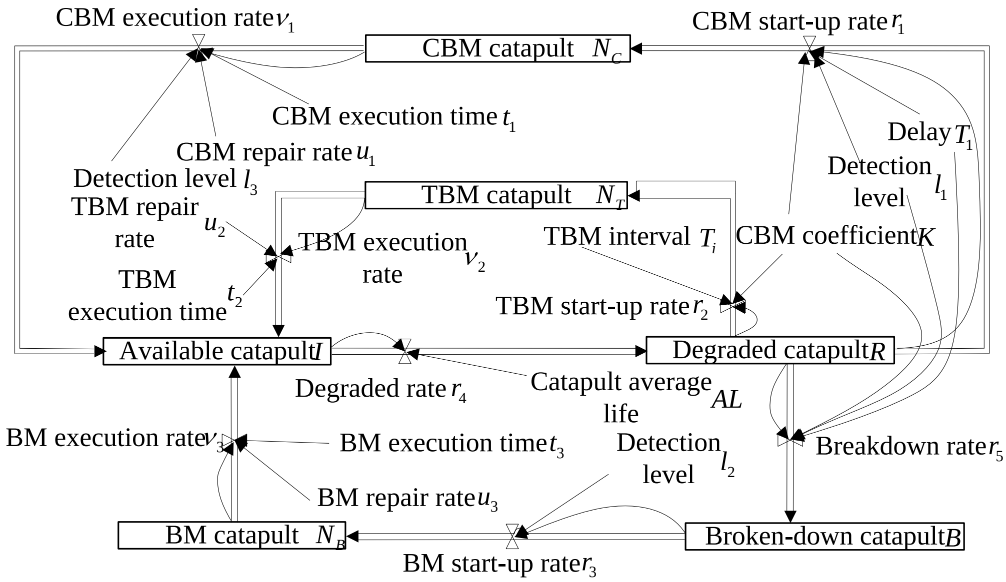

Figure 3. Flow Diagram of the Catapult Availability System Considering CBM

3.3. Expressions of System Model

Figure 3 can describe the cause and effect relationship and system structure of the system elements. But it cannot show the quantitative relationship between the system variables. It cannot fully quantitatively describe the dynamic behavior of the system. So it is further described by structural equations.

State equation of available catapult I can be obtained from Figure 3.

$$I(t)=I(t-\Delta t)+[v_1(t-\Delta t)+v_2(t-\Delta t)+v_3(t-\Delta t)-r_4(t-\Delta t)]\cdot\Delta t \quad (1)$$

There is a state variable of degraded catapult R between the degraded rate r_4 and broken-down rate r_5. It denotes the number of catapult at a certain moment detected in potential broken-down condition between point P and point, rate of the input. Its input rate is r_4 and output rate is r_5. State equation of degraded catapult R can be obtained.

$$R(t)=R(t-\Delta t)+[r_4(t-\Delta t)-r_1(t-\Delta t)-r_2(t-\Delta t)-r_5(t-\Delta t)]\cdot\Delta t \quad (2)$$

State equation of broken-down catapult B is

$$B(t)=B(t-\Delta t)+[r_5(t-\Delta t)-r_3(t-\Delta t)]\cdot\Delta t \quad (3)$$

State equation of CBM start-up catapult N_C is

$$N_C(t)=N_C(t-\Delta t)+[r_1(t-\Delta t)-v_1(t-\Delta t)]\cdot\Delta t \quad (4)$$

State equation of TBM start-up catapult N_T is

$$N_T(t)=N_T(t-\Delta t)+[r_2(t-\Delta t)-v_2(t-\Delta t)]\cdot\Delta t \quad (5)$$

State equation of BM start-up catapult N_B is

$$N_B(t)=N_B(t-\Delta t)+[r_3(t-\Delta t)-v_3(t-\Delta t)]\cdot\Delta t \quad (6)$$

In the initial condition, the catapult works normally. There is no potential breakdown and maintenance requirement. The number of degraded catapult $R(0)=0$. The number of broken-down catapult $B(0)=0$. The number of available catapult is equal to the number of initial catapult $I(0)=4$. The number of CBM start-up catapult $N_C(0)=0$. The number of TBM start-up catapult $N_T(0)=0$. The number of BM start-up catapult $N_B(0)=0$. If there is potential breakdown, the degraded rate $r_4>0$ and CBM and TBM are implemented when conditions permit. If the maintenance condition does not permit or there is no potential breakdown detected, the catapult degrades to breakdown due to continuing to use it and BM is implemented.

According to the accumulations of rates variable effecting on state variables, the following equation can be obtained.

The rate equation of degraded rate r_4 is

$$r_4(t)=I(t)/AL \quad (7)$$

The rate equation of broken-down rate r_5 is

$$r_5(t)=(1-l_1)R(t)K/(T_1+T_2) \quad (8)$$

The rate equation of CBM start-up rate r_1 is

$$r_1(t)=l_1R(t)K/T_1 \quad (9)$$

The rate equation of CBM execution rate v_1 is

$$v_1(t)=l_3u_1N_C(t)/t_1 \quad (10)$$

The rate equation of TBM start-up rate r_2 is

$$r_2(t)=(1-K)R(t)/T_i \quad (11)$$

The rate equation of TBM execution rate v_2 is

$$v_2(t)=u_2N_T(t)/t_2 \quad (12)$$

The rate equation of BM start-up rate r_3 is

$$r_3(t)=l_2B(t) \quad (13)$$

The rate equation of BM execution rate v_3 is

$$v_3(t) = u_3 N_B(t) / t_3 \tag{14}$$

The expression of available catapult I about rate variable can be obtained from Eq. (7) and Eq. (1).

$$I(t) = [AL - \Delta t] r_4(t-\Delta t) + [v_1(t-\Delta t) + v_2(t-\Delta t) + v_3(t-\Delta t)] \cdot \Delta t \tag{15}$$

The expression of degraded catapult R about rate variable can be obtained from Eq. (8) and Eq. (2).

$$R(t) = [\frac{T_1 + T_2}{K(1-l_1)} - \Delta t] r_5(t-\Delta t) + [r_4(t-\Delta t) - r_1(t-\Delta t) - r_2(t-\Delta t)] \cdot \Delta t \tag{16}$$

The expression of broken-down catapult B about rate variable can be obtained from Eq. (13) and Eq. (3).

$$B(t) = [\frac{1}{l_2} - \Delta t] r_3(t-\Delta t) + r_5(t-\Delta t) \cdot \Delta t \tag{17}$$

The expression of CBM start-up catapult N_C about rate variable can be obtained from Eq. (10) and Eq. (4).

$$N_C(t) = [\frac{t_1}{l_3 u_1} - \Delta t] v_1(t-\Delta t) + r_1(t-\Delta t) \cdot \Delta t \tag{18}$$

The expression of TBM start-up catapult N_T about rate variable can be obtained from Eq. (12) and Eq. (5).

$$N_T(t) = [\frac{t_2}{u_2} - \Delta t] v_2(t-\Delta t) + r_2(t-\Delta t) \cdot \Delta t \tag{19}$$

The expression of BM start-up catapult N_B about rate variable can be obtained from Eq. (14) and Eq. (6).

$$N_B(t) = [\frac{t_3}{u_3} - \Delta t] v_3(t-\Delta t) + r_3(t-\Delta t) \cdot \Delta t \tag{20}$$

Finally, the relationship between the 6 state variables and 8 rate variables can be obtained.

$$\begin{bmatrix} I(t) \\ R(t) \\ B(t) \\ N_C(t) \\ N_T(t) \\ N_B(t) \end{bmatrix} = \begin{bmatrix} \Delta t & \Delta t & \Delta t & 0 & 0 & 0 & AL-\Delta t & 0 \\ 0 & 0 & 0 & -\Delta t & -\Delta t & 0 & \Delta t & \frac{T_1+T_2}{K(1-l_1)} - \Delta t \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{l_2} - \Delta t & 0 & \Delta t \\ \frac{t_1}{l_3 u_1} - \Delta t & 0 & 0 & \Delta t & 0 & 0 & 0 & 0 \\ 0 & \frac{t_2}{u_2} - \Delta t & 0 & 0 & \Delta t & 0 & 0 & 0 \\ 0 & 0 & \frac{t_3}{u_3} - \Delta t & 0 & 0 & \Delta t & 0 & 0 \end{bmatrix} \begin{bmatrix} v_1(t-\Delta t) \\ v_2(t-\Delta t) \\ v_3(t-\Delta t) \\ r_1(t-\Delta t) \\ r_2(t-\Delta t) \\ r_3(t-\Delta t) \\ r_4(t-\Delta t) \\ r_5(t-\Delta t) \end{bmatrix} \tag{21}$$

According to Figure 3, the function of CBM execution rate v_1, TBM execution rate v_2 and BM execution rate v_3 is to increase the number of available catapult. The function of degraded rate r_4 and broken-down rate r_5 is to decrease the number of available catapult I. Similarly, the function of CBM start-up rate r_1 is to increase the number of CBM execution catapult N_C. The function of TBM start-up rate r_2 is to increase the number of TBM execution catapult N_T. The function of BM start-up rate r_3 is to increase the number of BM execution catapult N_B. The degradation of catapult can meet the maintenance requirements. The function of CBM execution and BM execution is to decrease the number of degraded catapult R and broken-down catapult B.

It is shown from the above dynamic process analysis that the number of available catapult I can increase by CBM, TBM and BM. Then the readiness rate is improved. It is a positive feedback system with difference. In addition, the ability of condition monitoring, fault detection and diagnosis lead to the randomness of repair results. Therefore, the number of available catapult I is not constant. It fluctuates up and down according to the maintenance situation.

3.4. Analysis of Catapult Availability

The equation of available catapult U is

$$U(t) = I(t) = (AL - \Delta t)r_4(t - \Delta t) + [v_1(t - \Delta t) + v_2(t - \Delta t) + v_3(t - \Delta t)] \cdot \Delta t \quad (22)$$

The reasons tree structure of the change of the total number of available catapult is established by the structural analysis, as shown in Figure 4.

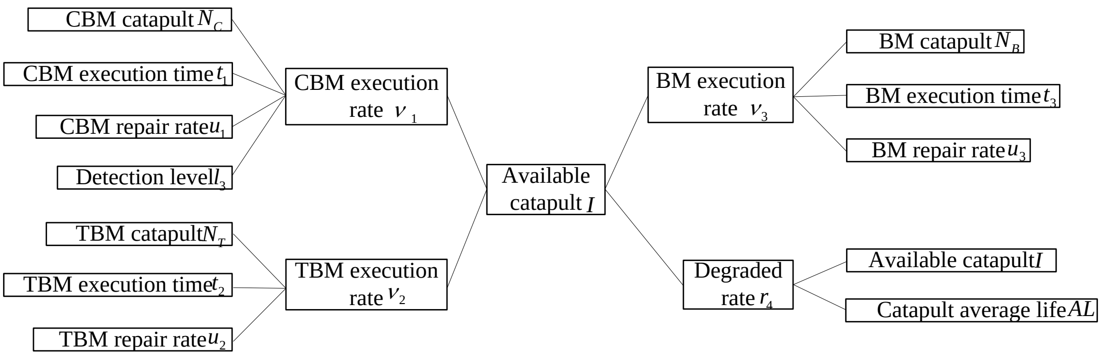

Figure 4. Factors Affecting the Number of Available Catapult

The factors that affect the number of available catapult are CBM execution rate, TBM execution rate, BM execution rate and degraded rate from Eq. (21) and Figure 4. There is a feedback loop as shown in Figure 4. The degraded rate is affected by the number of available catapult.

4. Analysis of Dynamic Simulation

This paper takes the catapult maintenance of the aircraft carrier "Nimitz" as the research object. The catapult maintenances of the aircraft carrier "Nimitz" are divided into once a year, once six months, once each quarter, once a month, once a week. The R-27 inspection weekly includes test of the open timer of ejection valve, capacity selection valve system and the inspection and lubrication of hydraulic brake parts. According to the operational guidelines 4790/85 of Naval Operations, these checks will need about 3 hours of work to complete. If the maintenance operations are required during the period of high intensity exercise, each R-27 check could reduce at least 2 cycles.

Table 1. Frequency of Catapult Periodic Maintenance

Type of Check	Interval of Check	Time of Periodic Maintenance
R-7	400-500 ejections	-
R-25	10000 ejections	-
R-16	100-200 ejections	15min
R-27	1 week	3 hours of work
Overhaul of C-13 catapult	15000 ejections	-

Assumed that there are 4 independent and similar catapults, the time of system simulation is 1000 unit time and the simulation step size is 1.

Aimed at the results of simulation with CBM coefficient K = 0.1, 0.3, 0.5, 0.3 and 0.9, the curves of the number of available catapult and catapult availability are shown in Figure 5 and Figure 6.

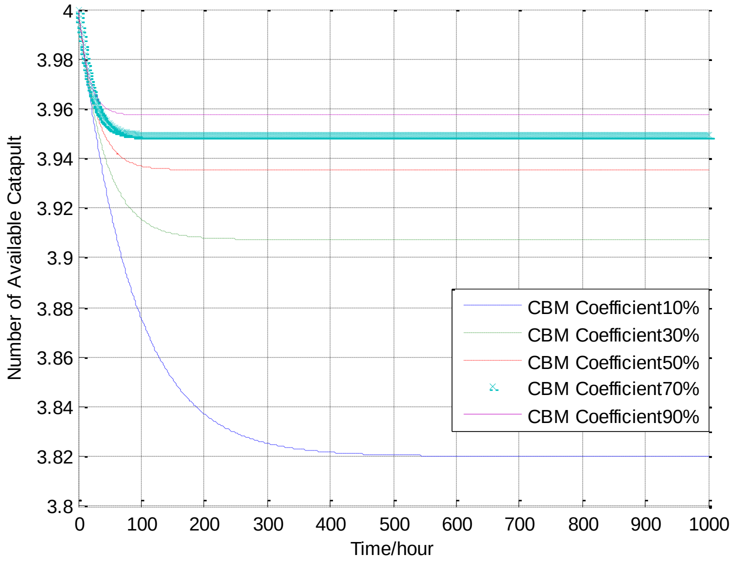

Figure 5. Number of Available Catapult

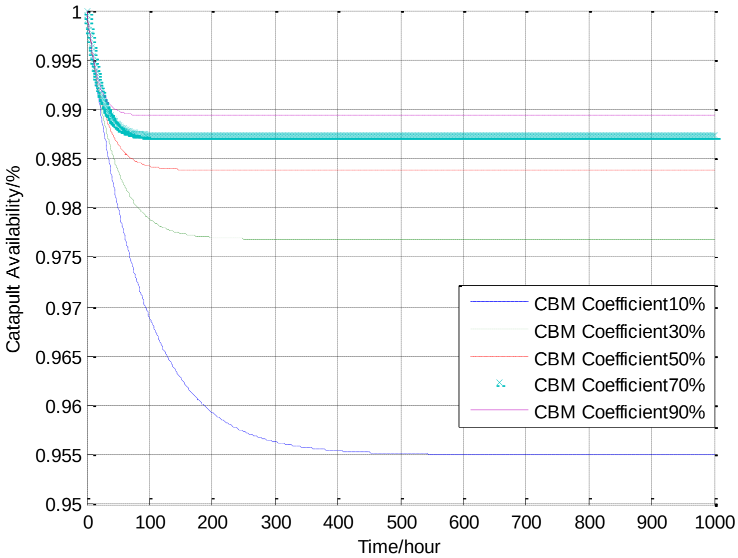

Figure 6. Catapult Availability

Figure 5 and Figure 6 show that as the increase of CBM coefficient, the number of available catapult will increase. So increasing CBM coefficient can increase the number of available catapult and catapult availability in the steady state. In the steady state, when CBM coefficient is 10%, the number of available catapult is 3.82 and the catapult availability is 95.51%. When CBM coefficient is 90%, the number of available catapult is 3.96 increased by 0.14 and the catapult availability is 98.94% increased by 3.43%.

Table 2. Comparison Table of Available Catapult

	K=10%	K=30%	K=50%	K=70%	K=90%
Number of available catapult	3.82	3.91	3.94	3.95	3.96
Increase of available catapult	0	0.09	0.12	0.13	0.14
Catapult availability (%)	95.51	97.69	98.39	98.73	98.94
Increase of catapult availability (%)	0	2.18	2.88	3.23	3.43

From Table 2, as the increase of CBM coefficient K, the velocity of available catapult increase will decrease. Therefore, considering economic and sustainability of work, the better CBM coefficient is 50%. The number of available catapult is 3.94 and the catapult availability is 98.39%. Compared with 10% CBM coefficient, the number of available catapult is increased by 0.12 and the catapult availability is increased by 2.88%. The increase is large. Compared with 90% CBM coefficient, the number of available catapult is decreased by 0.02 and the catapult availability is decreased by 0.55%. The decrease is small. Therefore, when CBM coefficient is 50% and 90%, the number of available catapult and the catapult availability are relatively close. But economic and sustainability of work are better with 50% CBM coefficient.

5. Conclusions

In this paper, catapult maintenance system model is established by using the principle of SD. It is based on the dynamic principle of catapult feedback control structure. A variety of system factors are considered. Through the simulation, the situations of available catapult, degraded catapult and broken-down catapult are shown. The above analysis shows that CBM turns Breakdown Maintenance into active maintenance based on state. The number of available catapult is significantly improved by improving CBM coefficient. The number of degraded catapult and broken-down catapult is effectively reduced. It can guarantee the catapult availability and reduce maintenance cost.

As the catapult is a complex aviation equipment maintenance system. The above maintenance mode has associated with TBM, CBM and BM. It can achieve the optimization process, efficiency of maintenance improvement, equipment availability improvement and maintenance cost reduction. It has very important practical significance for the navy catapult maintenance.

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