Research on Joint Optimization of Condition Inspection Interval and Spare Parts Inventory Strategy

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Abstract—**For the devices with condition inspections, the method for joint optimization of inspection interval and spare parts inventory strategy was studied. Firstly, the periodic inspection policy was introduced, based on which the spare parts consumption and provisioning process was analyzed; secondly, the cost structure of maintenance support was decomposed, and the mathematical models for total maintenance support cost were established; thirdly, a simulation method was proposed, by which the periodic inspection interval, spare parts maximum stock level and ordering interval could be optimized jointly; lastly, a numerical example was given, which demonstrated the optimization method and models above.**

Keywords-condition inspection; spare parts inventory; optimization; simulation

I. Introduction

Timely and effective condition inspection is a common and important measure to ensure safe and reliable operation for devices, and also an important basis for making up maintenance strategies and developing support decisions[1].

So far, the researches on device condition inspection are mostly used to evaluate the health status and grade, predict the remaining useful life and determine the maintenance type. However, the subsequent support decision-makings are seldom considered jointly. Thus, there will inevitably be delays in the support[2], and the optimal maintenance support effect can't be achieved[3].

For the devices with heavy shutdown loss, the maintenance mode of periodic condition inspection is usually adopted[4], that is, every other period of time, condition inspection is carried out, and maintenance actions and support strategies are determined by the operation condition of the device[5]. Under this condition-based maintenance strategy, how to analyze and quantitatively describe the process of spare parts consumption, and make up scientific spare parts inventory decision, has become a key problem needed to be studied and solved in the field of spare parts support.

Therefore, this paper carries out the optimization research of spare parts inventory strategy based on condition inspection information, describes the device function degradation process using relevant theories, analyses the inventory change characteristics in maintenance support, establishes the joint decision-making model of device inspection interval and spare parts inventory, and puts forward the optimization process and method. By which, the spare parts inventory level, condition inspection interval and inventory replenishment time can be optimized jointly.

II. Spare parts consumption process analysis under periodic inspection policy

Under the Condition-based Maintenance strategy, in order to prevent the devices from failure which causes great losses, the condition inspection is usually carried out. Once the potential failure is found, timely measures are taken to avoid the occurrence of functional failure. In this paper, on the basis of the commonly used spare parts periodic ordering strategy of (t_0, S) , the condition inspection interval T_n is also considered , which is named as (T_n, t_0, S) strategy.

The detailed meaning of (T_n, t_0, S) strategy is as follows: the initial spare parts inventory level is S, and the replenishment time is t_0. In the process of device operation, the condition inspection is carried out with the interval of T_n. If the device is found in good performance, it will remain in operation; else, if in deteriorating state, it will be replaced immediately with a spare part to prevent functional failure. When the device fails between two successive inspections, it will be replaced with a spare part, too. Once the timing of inventory replenishment arrives, spare part replacement is adopted to ensure the reliable operation of the device, and the inventory level is replenished to S.

It can be seen that, the timing of spare parts replacement under this strategy is different from that under the traditional periodic replacement strategy. There are three situations:

(1) By condition inspection, it is found that the device is still in good performance, and no replacement of spare part is carried out.

(2) By condition inspection, the potential failure is found, and the spare part replacement is carried out immediately.

(3) Before condition inspection, the functional failure occurs, and the spare part replacement is carried out immediately.

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Accordingly, spare parts inventory and ordering are also affected. Fig. 1 shows the spare parts inventory consumption process under periodic inspection strategy. Obviously, there are two situations during the ordering period.

Situation 1: the actual demand of spare parts during the ordering period is less than the inventory of spare parts, and there is still a surplus inventory when reaching the ordering time.

Situation 2: the actual demand of spare parts is larger than the inventory of spare parts, and there is a shortage before ordering.

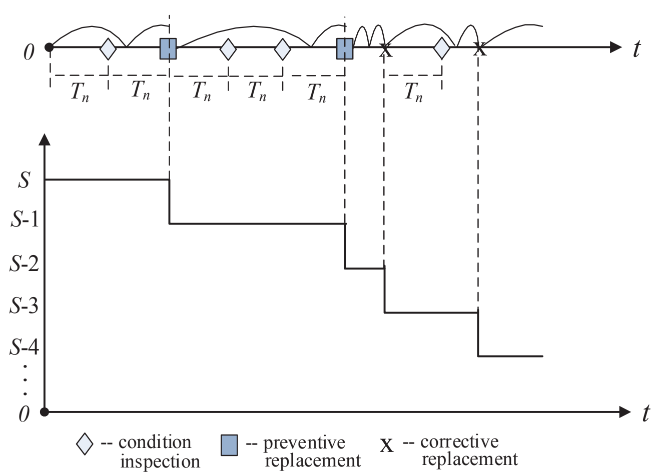

Figure 1. Spare parts consumption process under periodic inspection policy

The purpose of this paper is to obtain the inspection interval and spare parts inventory strategy by jointly optimizing three variables: maximum inventory level S, condition inspection interval T_n and inventory replenishment timing t_0, which can minimize the maintenance support cost per unit time.

III. Maintenance Support Cost Analysis and Modeling Based on Inspection Information

The two situations of spare parts inventory consumption process were analyzed above, and there are also two situations for maintenance support cost during spare parts supply correspondingly. One is that when the spare parts inventory is still surplus at the replenishment timing, the maintenance support costs include inspection cost, preventive replacement cost, corrective replacement cost, storage cost, ordering cost, spare parts cost; the other is that when the spare parts inventory is run out of before the replenishment timing, the costs also include stock shortage loss in addition to six kinds of costs in the above situation.

So, the key problem is to analyze and model the maintenance and support costs in the two situations above. Assuming that the cost for each condition inspection, preventive replacement, corrective replacement are denoted by c_n, c_p , c_f respectively; and the cost for each spare part storage per unit time, spare part ordering, each spare part, stock shortage loss per unit time are denoted by c_h, c_o, c_b, c_{los} respectively. The modeling method of maintenance support cost is as follows.

(1) Cost model in the situation of adequate inventory

If the spare parts inventory is surplus during the ordering period (0, t_0) , the total inspection times N_i, the timing of each replacement K_j and the total number of spare parts consumption N (among which the preventive and corrective replacement times are N_p and N_f, respectively) can be obtained.

Accordingly, the costs can be expressed as:

cost of condition inspection $C_n = c_n \cdot N_i$

cost of preventive replacement $C_p = c_p \cdot N_p$

cost of corrective replacement $C_f = c_f \cdot N_f$

cost of spare parts ordering $C_o = c_o + (N+1) \cdot c_b$

cost of spare parts storage

$$C_h = \left[K_1 + K_2 + \cdots + K_N + (S - N) \cdot t_0\right] \cdot c_h$$

Added by the preventive replacement cost of c_p when replenishing stock, the total maintenance support cost during the ordering period can be expressed as:

$$\begin{aligned} C_{Total} &= c_n \cdot N_i + c_p \cdot N_p + c_f \cdot N_f + c_o + (N+1) \cdot c_b \\ &+ \left[K_1 + K_2 + \cdots + K_N + (S-N) \cdot t_0\right] \cdot c_h + c_p \end{aligned}$$

(2) Cost model in the situation of inadequate inventory

If the spare parts has been run out of before t_0, it's evident that the total number of spare parts consumption N equals S. Similarly, the total inspection times N_i, the timing of each replacement K_j, the preventive replacement N_p and the corrective replacement times N_f can be obtained.

Accordingly, the costs can be expressed as:

cost of condition inspection $C_n = c_n \cdot N_i$

cost of preventive replacement $C_p = c_p \cdot N_p$

cost of corrective replacement $C_f = c_f \cdot N_f$

cost of spare parts ordering $C_o = c_o + (S+1) \cdot c_b$

cost of spare parts storage

$$C_h = \left[K_1 + K_2 + \cdots + K_S\right] \cdot c_h$$

cost of stock shortage loss $C_{los} = (t_0 - K_{S+1}) \cdot c_{los}$

Added by the preventive replacement cost c_p when replenishing stock, the total maintenance support cost during the ordering period can be expressed as:

$$\begin{aligned} C_{Total} &= c_n \cdot N_i + c_p \cdot N_p + c_f \cdot N_f + c_o + (S+1) \cdot c_b \\ &+ \left[K_1 + K_2 + \cdots + K_S\right] \cdot c_h + (t_0 - K_{S+1}) \cdot c_{los} + c_p \end{aligned}$$

IV. Simulation Calculation of Maintenance Support Cost

Due to the complexity of spare parts inventory consumption process, it is difficult for analytical modeling. In this paper, the above process is described and quantified by simulation.

In order to scientifically describe the device deterioration rule, the concept of "delay time" is introduced here[6].

According to the concept of delay time, the failure process can be divided into two stages: potential failure stage (0, u) and delay time stage (u, $u+h$). If the device is found in the first stage, it should be replaced preventively. If the delay time is too short to develop into functional failure before the next inspection, the device should be replaced once the failure happens, as shown in Fig.2 below.

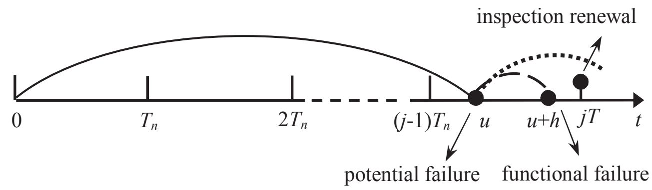

Figure 2. Periodic inspection policy based on delay time

The main steps are as follows (see Fig.3):

Step 1: Initialize simulation process and parameters. According to actual usage of the device, the distribution functions and parameters for potential failure and functional failure time, maximum inventory level S, condition inspection interval T_n and inventory replenishment timing t_0 are given for simulation optimization of the subsequent process.

Step 2: Generate the potential failure and delay time of the first spare part. By running the computer program, the potential failure time u and delay time h can be obtained, through which its real life t can be known as $u+h$.

Step 3: Judge its operation and maintenance situation under condition inspection strategy. If $t < T_n$, it means that it can't last until the first following inspection, and will break down at t. Thus, a corrective replacement is incurred, which needs a spare part. So the value of N_f will increase by 1, and the cumulative working time of device t_S will increase by t. On the contrary, it is necessary to judge whether this spare part are replaced by inspection or failure.

Step 4: If $t \geq T_n$, and judge the relationship between u and T_n. If $u < T_n$, it shows that potential failure can be found by the first condition inspection, the corresponding preventive replacement will increase the value of N_p by 1, and cumulative working time t_S will increase by T_n. Otherwise, it is still necessary to judge the subsequent replacement according to the value of h.

Step 5: Let $Z=\lfloor u/Tn \rfloor$, if $u+h > (Z+1)T_n$, it means that the potential failure can be found by the Zth condition inspection, the corresponding preventive replacement will increase the value of N_p by 1, and cumulative working time t_S will increase by $(Z+1)T_n$. Otherwise, it means that the functional failure will occur before the (Z+1)th condition inspection, the corresponding corrective replacement will increase the value of N_f by 1, and cumulative working time t_S will increase by t.

Step 6: Continue to generate random number of u and h, until the device reaches the time of inventory replenishment. In this way, the maintenance and support cost of the spare parts system of the device can be calculated according to the mathematical model established above.

Step 7: Repeat the above simulation steps for device operation and spare parts consumption M times, and the corresponding cost simulation results C_{Total}^{m} $\left(m = 1,2,\cdots,M\right)$ can be statistically processed. So the expected maintenance support cost per unit time of the spare parts system can be expressed as $EC = \sum_{m=1}^{M} C_{Total}^{m} \Big/ \left(M \cdot t_0\right)$.

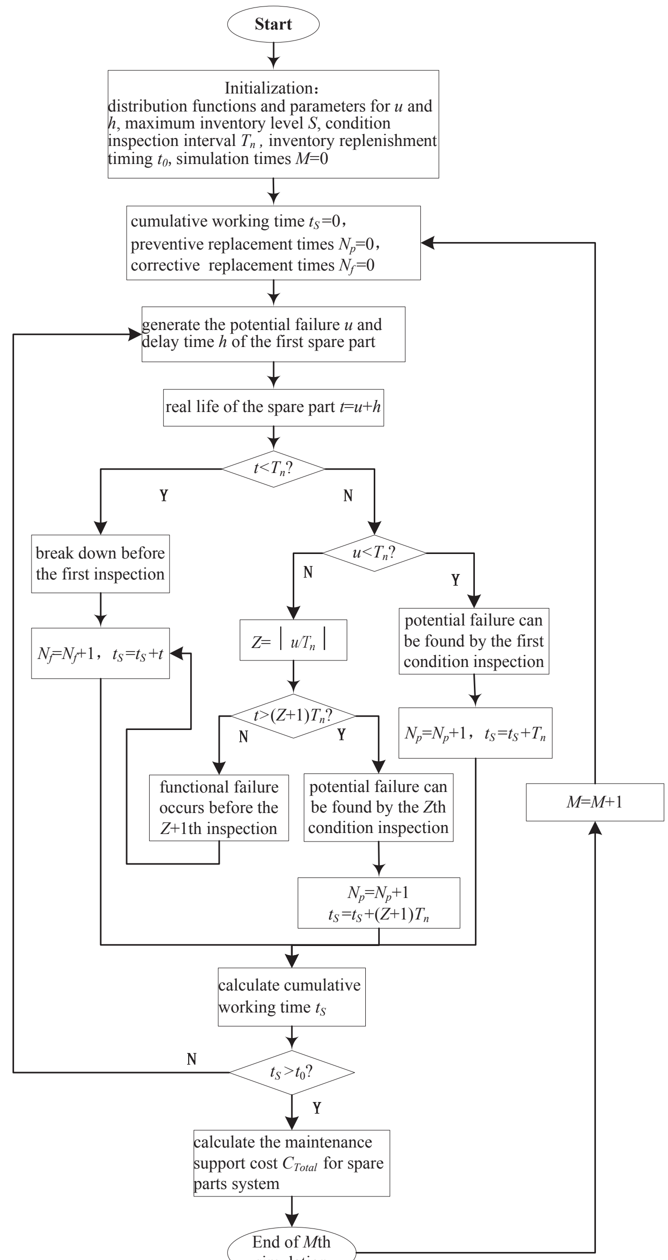

Figure 3. Spare parts consumption simulation under periodic inspection policy

V. A NUMERICAL EXAMPLE

To verify the validity of above model, a numerical example is given here. Assuming that the device with a performance degradation process is suitable for Condition-Based Maintenance strategy, and it initial defect time and delay time both follow Gamma distribution (with scale parameter α and shape parameter β). The parameters and cost values are shown in Table 1 below.

Table 1. The numerical example parameters

parameters	c_n	c_p	c_f	c_h	c_o	c_b	c_{los}	***u***		***h***	
								α_u	β_u	α_h	β_h
value	100	1000	5000	50	200	100	2000	50	3	40	3
unit	CNY	CNY	CNY	CNY/ day	CNY	CNY	CNY/ day	day	--	day	--

Then the computer is used to simulate the spare parts consumption and replenishment process, and the times of simulation N is 3000. Thus the maintenance support cost of spare parts system can be obtained, based on which the decision variables can be optimized further.

The objective of joint optimization is to determine three optimal variables, which are periodic inspection interval T_n, spare parts maximum stock level S and ordering interval t_0, which can minimize the total maintenance support cost per unit time. In this paper, MATLAB R2011b is used for iterative simulation. As is shown in Table 2, when t_0=280 days, S=3, and T_n=90 days, the maintenance support cost per unit time can be minimized, which reaches 208.0929 CNY/day.

Table 2. The optimization of total maintenance support cost

t_0 **(day)**	S	T_n **(day)**	EC **(CNY/day)**
200	2	80	314.8144
220	3	60	280.7312
240	3	70	247.0389
260	3	80	211.4393
280	3	90	208.0929
300	4	70	208.6605
320	4	80	214.8291
340	4	80	224.6984

Further, it can be seen that, with the change of three optimal variables, the total maintenance support cost reaches different value, which means the effect of spare parts support changes. So the joint optimization of inspection interval and spare parts inventory strategy is necessary and effective.

VI. CONCLUSIONS

In this paper, for devices with periodic condition inspection, a joint optimization model of Condition-Based Maintenance and spare parts inventory strategy was presented. The spare parts consumption and provisioning process was analyzed, the cost structure of maintenance support was decomposed, the mathematical models for total maintenance support cost were established, and the simulation calculation method was proposed. Finally, a numerical example was given, by which the periodic inspection interval, spare parts maximum stock level and ordering interval were optimized jointly.

However, the optimization algorithm given in this paper isn't efficient satisfactorily. So the related intelligent algorithm, such as genetic algorithm, ant colony optimization, and so on, could be explored in future.

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