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A timing decision-making method for product and its key components in proactive remanufacturing

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Abstract

Generally, the economic profits in product using are considered as the main factor in decision-making in remanufacturing. Since used key components are identified as the core in remanufacturing, each component and its own condition should be considered in decision-making. Thus, with mapping the relationship between product performance and its key components failure condition, a timing decision-making method in proactive remanufacturing is presented to conduct the remanufacturing with low consuming per year. Moreover, the remanufacturability of key components at the time with low consumption per year is evaluated. Finally, a diesel engine is given as an instance to validate the method.

Keywords: Optimization design; Structural strength parameter; Proactive remanufacturing; Remanufacturing timing

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1. Introduction

Considering the design and management of the products' lifecycle, green remanufacturing engineering is a series of technical measures and engineering activities, such as repair and transformation of the used products with high quality, high efficiency, energy conservation and environmental protection [1].Because of the uneven uncertainty of the cores, the cores are often remanufactured with individual and characteristically performance in the enterprises. For this issue, the concept of proactive remanufacturing is proposed. In using stage, the products are remanufactured in the identified time in order to achieve optimized efficiency and benefits.

For the timing decision-making problem in remanufacturing, lots of studies have been done. OKUMURA et al. optimized the product design in its cycle life based on remanufacturing theory [2]. Zhichao Liu conducted a comparative life cycle assessment of an original manufactured diesel engine with a remanufactured counterpart based on E-Balance software, and evaluated the optical time for the diesel engine remanufacturing [3]. Yawei Hu studied on the remanufacturing decision making with estimating the probability density distribution curve of the residual life by particle filter algorithm [4]. Liu Ming analyzed the mapping relationship between components failure condition and there manufacturability with the rules of components performance degradation [5].Yao gave some relative concepts about the remanufacturability based on total remanufacturing process [6].Shanshan Zhou established the index of the comprehensive average cost of the heavy truck engine based on life cycle cost and environmental cost, to identify the optimal remanufacturing time point [7]. Sundin .E et al. described how to achieve a successful remanufacturing process with an efficient take-back system and good product designs [8] . In these studies, it has not considered that the key components, which are the remanufacturing objects, have different failures conditions, and each component has its own remanufacturability. Thus, the proactive remanufacturing is presented and a timing decision-making method for product and its key components is presented in this paper.

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2. Proactive remanufacturing for product

2.1. Proactive remanufacturing

With considering the performance and function of product, proactive remanufacturing engineering is the series of engineering activities to actively remanufacture the products in the using stage with high quality, high efficiency, energy conservation, material conservation, environmental protection and long using time for products [9]. In current remanufacturing engineering, wasted products are considered as the remanufacturing cores, while the end-of-life time is the remanufacturing time. Since most the key components of wasted product is often overused, even broken with serious failure condition, the remanufacturability of end-of-life products are low, with the high cost for remanufacturing, and the loss of residual value. Meanwhile, due to the uncertainty of the ‘core’, the cost would be increased. Thus, in order to make full use of product residual value and eliminate the uncertainty of the cores, product should be remanufactured at some time interval (T_{AR}) before the end-of-life time. In proactive remanufacturing, when the products are remanufactured at the setting time interval, the product performance, including economic benefits, technical requirements, environmental emissions, etc. could be the best in the whole life cycle.

2.2. Mapping relationship

Mostly, the economic profits in product using are considered as the main factor in decision-making in remanufacturing. Since used key components, which are identified as the core in remanufacturing, have different failures conditions, it should consider the performance or failure condition in decision-making. If all components of product are remanufactured at the same time, some components could be still working ad not suitable for remanufacturing, while some over-used components just lost their remanufacturing value. Therefore, the remanufacturing time point of each component might be different. And to identify the remanufacturing time point of each component, the mapping relation between product performance and its key components failure condition should be analyzed.

Product performance is the integration of the function and quality, and the quality also is considered as the implement and perdurability of function. And the product performance is identified as the set of product’s function. Product performance is often supported by multiple components, that is to say, components are the functional supporters of products. Components and their function are indispensability of each other and constitute an organic unity of product function [10]. And every component has different relationship with product function. When some components are failure, product performance might decline. With analyzing the structure of the product, the relationship between product performance and its key components performance ($P(\sigma_1)$,$P(\sigma_2)$,$P(\sigma_3)$, ... ,$P(\sigma_n)$) is set up. And the variation of product performance is depending on its key components performance and failure condition (as shown in 1).

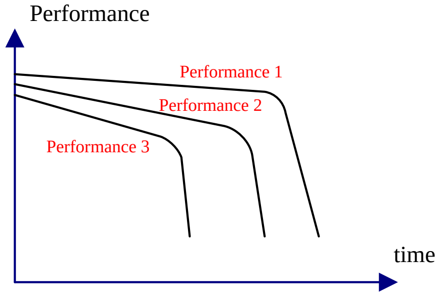

Figure 1Variation of component performance

2.3. Quantitative model of remanufacturability

Remanufacturing engineering and failure analysis are two independent disciplines, each of which has its theoretical basis. To quantify the remanufacturability of key components, the residual strength theory is given [11].

The residual strength (Rs) can identified as a parameter which characterizes the remanufacturability of key components in strength. According to the main failure modes of components, several strength indexes related to the residual strength (Rs) can be obtained. To describe the relative dimension of Rs, the residual strength factor is introduced. The residual strength factor of components remanufactured at time t can be described:

$$r_j(t) = \frac{D^j - D_1^{\,j}(t) + H(t)}{D_0^{\,j}} \qquad （2.1）$$

Among above, Dj donates the allowed maximum cumulative damage defined in design for components ; D1j(t) donates the loss strength of components after time t ,thus, the residual strength is D-D1(t); D0j donates the loss strength after a life-cycle period; H(t) donates restoring strength of components which are remanufactured according to their damage conditions.

From the aspect of design, with the variable performance of components in three stages: manufacturing, using and remanufacturing, if the residual strength factor r ⩾ 1, components have remanufacturing value. Considering the sake of the security, the residual strength factors should be multiplied by a factor of safety: r⩾1.25.

3. Time decision-making with product performance

3.1. Time decision-making

Proactive remanufacturing is product-oriented, not component-oriented. Since the product is composed of multiple components, there are some key components with the high value and some other components that should be replaced in the process of remanufacturing. Thus, the remanufacturability of key components must be considered.

First, with energy consuming quantified in three phases: manufacturing, using and remanufacturing, a function about the consumption per year is set up, and the remanufacturability of key components is analysed. Generally, the time $t_{0,}$ when consumption per year goes the lowest, is near the remanufacturing criticaltime point t_1 of key components. If remanufacturability of the key components is reasonable, then t_0 is the active remanufacturing timing; Otherwise, the remanufacturing critical point t_1 of key components should be analysed. Since $t_1 \leq t_0$, t_1 is the active remanufacturing timing with the reasonable remanufacturability of key components and the lower consumption per year.

3.2.Energy consumption

3.2.1 Consumption in the manufacturing stage

Generally, because of the tiny discrepancy of consumption for same-type product, the consumption in manufacturing stage is regarded as a constant. Based on the practical production process, the consumption in manufacturing stage is divided into two parts: one part is the consumption for the rough E_b, another is the consumption for machining E_{manu}.

The process of the rough includes extraction, forging and casting of the raw materials. If types of the material is n ($n \in N^+$), accordingly, the quality of material $i(i \leq n, i \in N^+)$ is m_i. The consumption for extraction of material i per unit mass is e_{mi}. The consumption for forging of raw material i per unit mass is e_{ci}, and The consumption for casting of raw material i per unit mass is e_{fi} . Thus, the consumption for the rough E_b can be described by

$$E_b = \sum_{i=1}^{n} m_i (e_{mi} + e_{ci} + e_{fi}) \qquad (i = 1,2,3,\cdots,n) \tag{3.1}$$

The consumption for machining is the consumption for transforming the rough into the product by machining system. If the number of processes is m($m \in N^+$), accordingly, the specific energy consumption of process j($j \leq m$， $j \in N^+$) is e_j, and the material removing rate of process j is k_j. Thus, the consumption for machining can be described by [3]

$$E_{manu} = \sum_{j=1}^{m} e_j \times k_i \times (m_{j-1} - m_j) \qquad (j = 1,2,\cdots,m) \tag{3.2}$$

Among above, m_j donates the quality of components after process j; m_{j-1}donates the quality of components before process j.

3.2.2 consumption in the using stage

With the decline of product performance over time, the consumption in the using stage could increase. If product has n key components, the consumption function of key component i because of its degradation of characteristic parameter is $e_i(\delta,t)$, among which δ is the variation of characteristic parameter. Thus, the consumption in the using stage in t years can be described by

$$Es(t) = \sum_{i=1}^{n} \int_0^t e_i(\delta,t)dt \tag{3.3}$$

3.2.3Consumption in the remanufacturing stage

Remanufacturing process generally includes disassembly, cleaning, preliminary inspection, repair, subsequent process, inspection to storage and reassembly, among which the consumption for such processes as disassembly, cleaning, preliminary inspection, subsequent process, inspection to storage and reassembly can be regarded as a constant. Meanwhile, with the variation of key components characteristic parameters, the consumption for remanufacturing repair increases with the passing of time. If the product consists of u ($u \in N^+$) key components, the consumption for disassembly, cleaning, inspection, subsequent process, reassembly of component k ($k \leq u$， $k \in N^+$) is T_k. In repair process, the volume of remanufacturing repair is $V_k(\delta,t)$, and the consumption for remanufacturing repair per unit volume is e_R. Thus, the consumption in the remanufacturing stage can be described by

$$E_R(t) = \sum_{k=1}^{u} \left[T_k + V_k(\delta,t) e_R \right] \tag{3.4}$$

As the evaluation index for time decision-making for proactive remanufacturing, the consumption per year can be described by

$$f(t) = \frac{E}{t} = \frac{\sum_{i=1}^{n} e_{mi}(D_i) + \int_0^t e_s(\delta,t)dt + \sum_{j=1}^{m} e_R(\Delta_j, D_j)}{t} \tag{3.5}$$

4. Case study

A single cylinder diesel engine is selected as the study object. With the application of energy analysing in life cycle, a timing decision-making method in proactive remanufacturing is presented.

4.1 Consumption in the manufacturing stage

Tab 4.1 Quality parameters of a certain type of diesel engine major parts[12]

NO.	name	material	density*(kg/ m³)*	quality *（kg）*
1	cylinder block and head	cast-iron	7850	125.5
2	cylinder liner	45	7850	2.3600
3	crankshaft	QT60-2	7850	13.06
4	connecting rod shank	45	7850	1.423
5	connecting rod cap	45	7850	0.467
6	piston	ZL8	2890	0.877
7	wrist pin	20Cr	7820	0.360

With the reference of the literature[3][13-15], Combining formulas（3.1）（3.2）with table 4.1, the consumption for manufacturing cylinder block and head, cylinder liner, crankshaft and connecting rod is 2172、38.23、25.18、226.2、30.61（kWh）respectively .

4.2 Consumption in the using stage

In the diesel engine combustion system, the slider-crank mechanism consists of crankshaft, connecting rod, piston and cylinder, which transfers the rectilinear motion into circular motion.

Generally speaking, with the failure of components, the performance of product declines. In these key components, crankshaft and piston might be failure in high possibility. With the passing time in using stage, the wear mass loss of the crankshaft increases gradually. The original mechanism evolves into a slider-crank mechanism with clearance, which leads to the collision between the crankshaft with the connecting rod during runtime, the decline of the running accuracy of the mechanism and the decrease of output torque of the mechanism. Meanwhile, in the using stage, the inner wall of the cylinder could wear, which leads to the decrease of the sealing of the space constituted by the piston and the cylinder, the leakage in combustion and the drop of the pressure in the cylinder.

4.2.1 Clearance of crankshaft—consumption

The wearing is one of the most common, most important failure factors in mechanical motion pair. It might not only leads to the noise and vibration, but also bring the hidden trouble for equipment. The common failure areas of the crankshaft are at the trunnion and the rod journal which impact most on the running accuracy of the mechanism. With the rod journal wearing, the output torque of the mechanism could decline. The slider-crank mechanism with clearance is shown in figure 4.1.

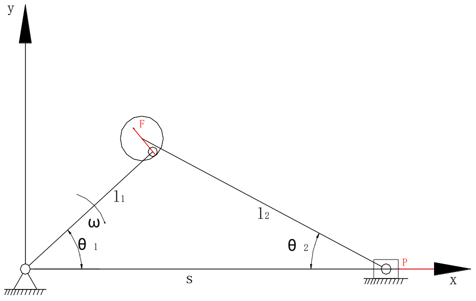

Figure 2The slider-crank mechanism with clearance

As shown in figure 2, there exists wear clearance between the rod journal and the connecting-rod bearing. During the motion, since the collision between the rod journal and the connecting-rod bearing, the uncertainty and the bounce of the relative location occur, this leads to the difficulty for obtaining the output torque. Thus, in this paper, the assumption that the force on the rod journal always perpendiculars to the crankshaft is set, with the maximum of the output torque. The output torque can be described by:

$$M = \frac{p\pi D^2 l_1}{4\cos\theta_2}\sin(\theta_1+\theta_2) \qquad （4.1）$$

Geometric relationships:

$$(l_1 + \frac{e}{\tan(\theta_1+\theta_2)})\sin\theta_1 = (l_2 - \frac{e}{\sin(\theta_1+\theta_2)})\sin\theta_2 \qquad （4.2）$$

Equation of state of ideal gas:

$$p_0 l_0 = p\left[l_0 + (l_1 + \frac{e}{\tan(\theta_1+\theta_2)})(1-\cos\theta_1) + (l_2 - \frac{e}{\sin(\theta_1+\theta_2)})(1-\cos\theta_2)\right] \qquad (4.3)$$

in figure3.

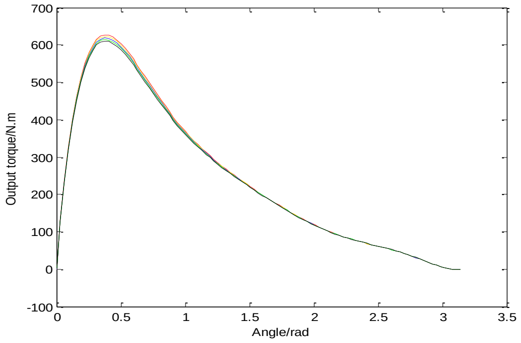

Figure 3Variation of the output torque

To assure enough output torque, it needs extra energy for the diesel engine. With the rated speed 2200r/min, the consumption (kWh) with the rod journal wearing is:

$$Q_{u1}(t) = 16600w(t)^2 + 1660w(t) \qquad （4.4）$$

According to literature [16], the wearing rate of the rod journal (mm) is

$$w_1 = 0.010t \qquad （4.5）$$

Thus, the consumption (kWh) with the rod journal wearing in the using stage will be:

$$Q_{u1}(t) = 16.6t^2 + 16.6t \qquad （4.6）$$

4.2.2 Wear of the cylinder & piston—consumption

The cylinder wearing leads to the decrease of the sealing of the combustion space and the leakage in combustion. Based on the combustion model, the impact on the thermodynamic performance because of the leakage is analysed. According to Bernoulli equation, the leakage of the piston in a period can be described by[17]

$$m_{Gap\text{-}ring} = \int_{\varphi_{VB}}^{\varphi_{VB}+\Delta\varphi} \rho A_b \sqrt{\frac{2\Delta p}{\rho}}\, d\varphi \qquad （4.7）$$

Among above, Δp donates the difference in pressure between the cylinder and the crankcase. In the combustion stage, the pressure in the crankcase is the atmospheric pressure (0.101Mpa), while the pressure in the cylinder can go up to 8 Mpa, both of which differ bigger. Thus, Δp can be regarded as the pressure in the cylinder; A_b donates the equivalent leakage area: $A_b = \pi D \delta$, among, D donates the cylinder bore, δ

donates the equivalent leakage clearance, ρ donates the refrigerant density.

Equation of state of ideal gas:

$$pM = \rho RT \quad （4.8）$$

Weiber function:

$$\frac{dQ_b}{d\varphi} = 6.908\frac{\eta_u m_b H_u}{\Delta\varphi}(m+1)\left(\frac{\varphi-\varphi_{VB}}{\Delta\varphi}\right)^m \exp\left[-6.908\left(\frac{\varphi-\varphi_{VB}}{\Delta\varphi}\right)^{m+1}\right] \quad (4.9)$$

At the rated speed 2200r/min, the consumption (kWh) with the cylinder wearing is:

$$Q_{u2}(t) = 50323.5w_2(t)^2 + 6441.4w_2(t) \quad (4.10)$$

According to literature [18], the wearing rate of cylinder (mm) is

$$w_2(t)=0.128t \quad (4.11)$$

Consumption (kWh) with the cylinder wearing in the using stage will be:

$$Q_{u2}(t) = 824.5t^2 + 824.5t \quad (4.12)$$

4.3 Consumption in the remanufacturing stage

Considering the higher manufacturing cost and the lower remanufacturing cost, the crankshaft and the connecting rod should be remanufactured. Meanwhile, the piston and the cylinder liner could be replaced with the low manufacturing cost. And the consumption in the remanufacturing stage includes the consumption for remanufacturing crankshaft, replacing piston and cylinder liner.

Crankshaft remanufacturing includes a serial of processes as cleaning, inspection, restore and subsequent process and so on. The restoring process is laser spraying with the nichrome material. Thus, the consumption for repair process consists of the consumption for the extraction of the nichrome and the power consumption for spaying.

According to the data provided by lecture [3], the consumption for remanufacturing processes of the crankshaft is 1.611, 0.886, 8.49t+1.5, 6.615 respectively. Besides, the consumption for replacing the piston and the cylinder liner is its manufacturing consumption.

4.4 Active Remanufacturing Timing Determination

4.4.1 Calculating the time with the lowest consumption per year

As stated earlier, it would wear mush faster in the cylinders than in the crankshaft. Thus, the cylinder should be replaced, while the crank should be remanufactured. And there are differences between the cylinder replacement time point and the crankshaft remanufacturing time point. To decrease the number of disassembly, the crankshaft remanufacturing time point t_R is supposed to the integer multiple cylinder replacement time point t_0:

$$t_R = nt_0 (n = 1.2.3...)$$

Combining the consumption in manufacturing, using, remanufacturing stage by calculating, the consumption per year in life cycle of the crankshaft and the cylinder can be described respectively by

$$f_1(t) = \frac{256.8 + 16.6t^2 + 16.6t + 8.49t + 10.612}{t} \quad （4.13）$$

$$f_2(t) = \frac{2235.52 + 824.5t^2 + 824.5t + 63.41}{t} \quad （4.14）$$

According to the model, the carve of the consumption per year of the crankshaft and the cylinder like a parabola in arrange 0 to 10 year, which are shown in figure 4, 5.

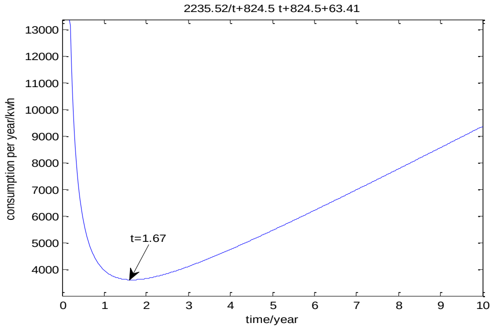

Figure 4Carve of the consumption per year of the crankshaft

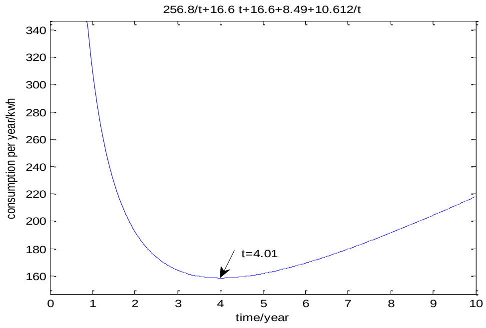

Figure 5Carve of the consumption per year of the cylinder

Because of much more consumption for the wear of the cylinder liner and the piston, the cylinder liner and the piston should be replaced in time. The replacing time t_0 of the cylinder liner and the piston is 1.67 years, while the remanufacturing time t_R of the crankshaft is 3.34 or 5.01 years.

6.4.2 Identifying the remanufacturability of component

At current level of technology, the abrasive damage of the crankshaft can be repair completely. With lecture [19], the repair limit of the crankshaft in this kind of engine is 0.25mm. Under normal use, the connecting rod journal of the crankshaft wears 10.4μm every year [16]. According to formula 2.1, the wear residual strength factor of the crankshaft at 3.34 and 5.01 year is 7.2 and 4.8,and both of them are larger than 1.25. Thus, the crankshaft has a great remanufacturing value at these two time point. With little difference of the consumption per year at these two time point, the remanufacturing time t_R of the crankshaft t_R is 5.01 years.

The variation of the remanufacturing diesel engine performance is shown in figure 4.5. As the easily damaged components, the replacing time of the cylinder liner and the piston is much earlier than the remanufacturing time of the crankshaft which is the wear-resistant component.

With the present calculation, the decline of the diesel engine performance because of the leakage of the cylinder is much more than that because of the wear of the crankshaft. Thus, with a replacement of the cylinder liner and the piston, the diesel engine performance could recover much, but not to the original value. With the third replacement of the cylinder liner and the piston and the remanufacturing of the crankshaft, the diesel engine performance could recover to the original value.

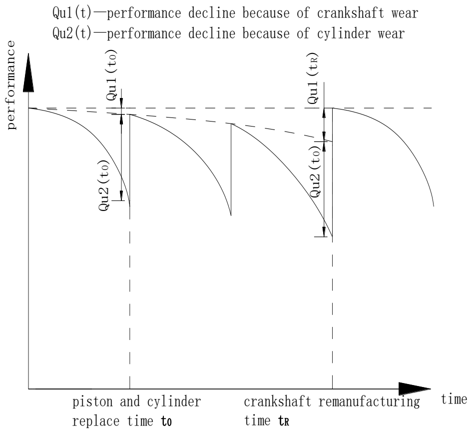

Figure 6 Variation of the remanufacturing diesel engine performance

5 SUMMARY

(1) With considering the uncertainty in quantity and quality of cores in end-of-life, the concept of proactive remanufacturing is presented.

(2) Based on the analysis of product consumption in life cycle and the remanufacturability of key components, a timing decision-making method in proactive remanufacturing is given.

(3) A diesel engine with the analysis of its crankshaft and cylinder is given as an instance to validate the method in this paper. The remanufacturing time t_R of the crankshaft t_R is 5.01 years, while the remanufacturing time t_0 of the piston and cylinder is 1.67 years.

Acknowledgements

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