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Reusable rocket engine preventive maintenance scheduling using genetic algorithm

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ABSTRACT

This paper deals with the preventive maintenance (PM) scheduling problem of reusable rocket engine (RRE), which is different from the ordinary repairable systems, by genetic algorithm. Three types of PM activities for RRE are considered and modeled by introducing the concept of effective age. The impacts of PM on all subsystems' aging processes are evaluated based on improvement factor model. Then the reliability of engine is formulated by considering the accumulated time effect. After that, optimization model subjected to reliability constraint is developed for RRE PM scheduling at fixed interval. The optimal PM combination is obtained by minimizing the total cost in the whole life cycle for a supposed engine. Numerical investigations indicate that the subsystem's intrinsic reliability characteristic and the improvement factor of maintain operations are the most important parameters in RRE's PM scheduling management.

1. Introduction

Maintenance is essential to keep a system in normal condition during the life cycle. For most systems, it could be classified into two categories, corrective maintenance (CM) and preventive maintenance (PM). CM is performed after failure to return the system to service as soon as possible. As for PM, it usually includes a well-defined set of tasks such as periodical inspection, cleaning, lubrication, adjusting, repairing of subcomponent and replacement, which help to enhance the state of the system by changing the age characteristic [1,2]. CM and PM are often carried out together to improve the reliability and availability of the system.

For a reusable rocket engine (RRE) like space shuttle main engine (SSME), which is designed to perform several flight tasks [3,4], the situation would be much different. Since RRE is retrievable after launch, by using RRE, the customers need not pay for a traditional expendable rocket engine each time, which is wasteful. The cost is reduced by sharing the total expense in an engine's service life. However, this means the engine has to survive all the prescribed flights, rendering high reliability a crucial requirement for RRE. From the view point of maintainability engineering, the potential disastrous consequences of rocket engine failure would eliminate repair or corrective maintenance as a primary consideration. Moreover, CM could not even be incorporated in PM scheduling in this case for the succeeding explosion or destructive effect after failure. Concern would be with the trade-off between RRE's reliability and how much PM could afford.

PM scheduling often involves balancing between reliability and economic performance, and is especially complicated for complex system with many components. This topic has been extensively discussed in the past decades [2,5–14]. Researchers tackle this problem from two perspectives: one is to construct PM models using single-component deteriorating system, the other is to solve the multi-components PM scheduling problem on the basis of single-component PM techniques. Nakagawa [7] and Kijima [15] present notable research for PM models by introducing effective age notation, which is also called virtual age model. Component which benefits from PM can have an effective age less than its calendar age. Tsai and Wang [2] propose a method to evaluate the time-dependent effect of three typical PM actions on component reliability. Moghaddam and Usher [8] use the branch and bound method to plan PM and replacement activities for a repairable and maintainable complex system. A growing number of heuristic algorithms are employed for complex system PM scheduling to consider the trade-off between reliability and cost [16–19].

In this paper, given the characteristic of RRE mentioned above, an optimization model is developed for PM scheduling at fixed interval considering no CM. Basic genetic algorithm is modified to determine the optimal PM practice by minimizing the total cost under the system reliability constraint. The remainder of the paper is organized as follows. In Section 2, the system configuration of RRE is introduced.

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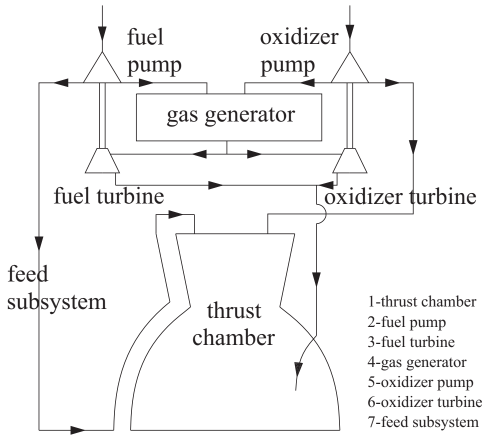

Fig. 1. Schematic of a RRE using gas generator cycle.

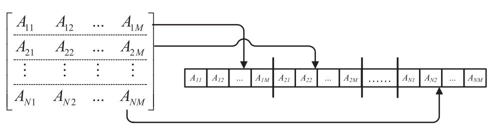

Fig. 2. Transformation process from design variable *A* to Integer-coded bit string of individual.

Section 3 gives a detailed description of optimization model for RRE PM scheduling. Three kinds of PM activities are taken into account simultaneously in this part. After that, subsystem's aging processes and time-dependent reliabilities are modeled. Section 4 is devoted to GA modification for solving the model. The computational results are then presented in Section 5. Some conclusion remarks are provided in Section 6.

2. System configuration

Fig. 1 shows the schematic of a typical RRE using gas generator cycle to be investigated in this paper. The whole engine can be divided into seven subsystems, i.e. thrust chamber, fuel pump, fuel turbine, gas generator, oxidizer pump, oxidizer turbine and feed subsystem. The feed subsystem includes piping, manifold, valves, actuator and other components. All the seven subsystems are labeled with a sequential number 1, 2, 3… 7 for reference.

In gas generator cycle the turbine inlet gas comes from a separate gas generator. Propellants (fuel and oxidizer) are supplied from separate propellant tanks by the feed subsystem respectively. The propellants go through pumps to be pressurized and then delivered into the thrust chamber. The thrust chamber is the combustion device where propellants are injected, atomized, mixed, and burned to form hot gaseous reaction products, which are in turn accelerated and ejected at a high velocity to impart a thrust force [20].

Since rocket engine is operated in very high pressure and high temperature environment, reliability has always been a fact of considerable concern. The situation is much more serious for RRE. We have to make the time-dependent reliability satisfy the requirement during all the appointed service life by taking appropriate PM activity combinations after each flight task. From the engineering viewpoint, the engine is ignited at the rocket launch and then shut down at a specified time T_0 for retrieving, which implies the PM is done at fixed interval.

Unlike the researches carried out in other civil mechanical products, RRE is not repairable if the system is broken-down. The prevailing assumption [7,8,14,18,19] in PM scheduling research that the failed system or subsystem undergoes minimal repair could not be used here. New methodology has to be developed to handle the problem.

Obviously, different PM activities have different impact on system's deteriorating process. In this paper, three typical PM actions introduced by Tsai [2] are taken into account to model the effects of maintenance to the engine. PM options are defined as follows:

(1) *Maintenance service* (MS): Several typical activities of MS are lubrication, cleaning, adjusting and replenishment of consuming materials. It can tune the subsystem to a better condition.
(2) *Maintenance repair* (MR): It generally includes the activities of MR and repairing/replacing for some simple parts, which recover the subsystem to a better state than MS.
(3) *Replacement* (RP): This type of action is to replace a subsystem with a new one which is adopted to avoid serious fault.

3. Optimization models for reusable rocket engine

Before proceeding to construct the optimization model for RRE, some general assumptions are listed below.

(1) Without loss of generality, RRE is assumed to be made up of *N* subsystems;
(2) the designed flight task number for RRE is *M*. PM can be carried out after each flight, namely, PM interval is T_0.
(3) The degradation of RRE is caused by regular start up, hot run and shut down in each flight task, while the transfer and storage after retrieve does not affect the aging characteristic of each subsystem;
(4) the failure time of subsystem *i* follows Weibull distribution with θ_i and β_i as scale and shape parameters, respectively, i.e., $T_i \sim Weibull(\theta_i, \beta_i)$;

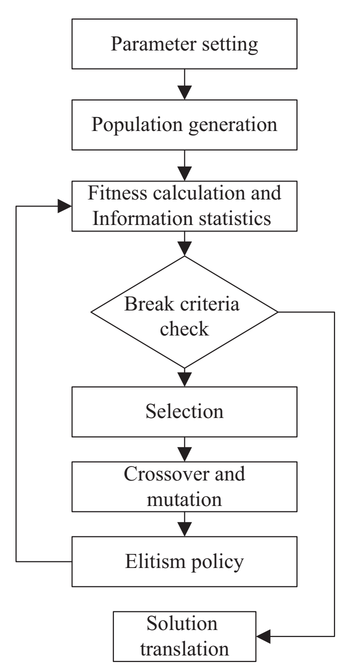

Fig. 3. The flow diagram of GA.