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Derating design for optimizing reliability and cost with an application to liquid rocket engines

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ABSTRACT

Derating is the operation of an item at a stress that is lower than its rated design value. Previous research has indicated that reliability can be increased from operational derating. In order to derate an item in field operation, however, an engineer must rate the design of the item at a stress level higher than the operational stress level, which increases the item's nominal failure rate and development costs. At present, there is no model available to quantify the cost and reliability that considers the design uprating as well as the operational derating. In this paper, we establish the reliability expression in terms of the derating level assuming that the nominal failure rate is constant with time for a fixed rated design value. The total development cost is expressed in terms of the rated design value and the number of tests necessary to demonstrate the reliability requirement. The properties of the optimal derating level are explained for maximizing the reliability or for minimizing the cost. As an example, the proposed model is applied to the design of liquid rocket engines.

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1. Introduction

In the early design stage, an engineer rates an item to withstand a certain amount of stress during operation. The failure rate of an item when operating at its rated value is called the nominal failure rate [4]. Derating is the operation of an item at a stress that is lower than its rated value so that its failure rate is lower than its nominal failure rate. Previous research has focused on increasing reliability from operational derating by deriving the failure rate in terms of thermal or electrical stress values [6,18] or calculating the reliability based on the stress strength model [8]. In order to derate the operation of an item, however, an engineer must rate design of the item at a stress level higher than the anticipated derated level, which increases the nominal failure rate. Therefore, a derating design is effective at enhancing the reliability only if the decrease in the failure rate from the operational derating is greater than the increase in the failure rate from the design uprating.

For example, an engineer may consider two options to design a capacitor that requires to withstand the voltage S under a fixed operating condition. First, the engineer rates the item to operate at S. In such a case, the failure rate of the item is the nominal failure rate A as given in Fig. 1(a). Second, the item can be designed with the derating level of $1-\alpha$, in which case the engineer rates an item at S/α for $0<\alpha<1$ and in field operation the item will operate at $100\alpha\%$ of its rated value. For example, if $\alpha=0.5$, we can say that the design rating is twice as high as the field operation rating or the field operation is at half of the design rating. As shown in Fig. 1 (a), the design uprating increases the nominal failure rate from A to B, while the operational derating decreases the failure rate from B to C. The derating design is preferred to obtain high reliability if the difference between B and A is smaller than the difference between B and C. The benefit of the derating design clearly depends on the several parameters such as the derating level, the ability of achieving the design uprating, and the amount of the failure reduction from the operational derating. However, there is no model available for quantifying the effect of derating design on the reliability.

A reliability optimization problem involves minimizing the cost function under a reliability requirement or maximizing the reliability under a cost constraint [2,17,25,26,28]. The cost is often considered separately from either the design [17,25] or the test viewpoint [2]. Recently, Ahmed and Chateauneuf [3] argued that

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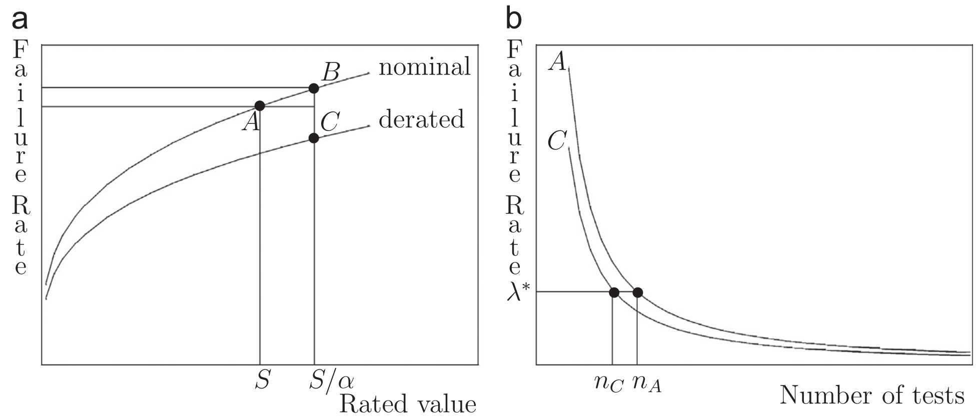

Fig. 1. Effect of derating design on failure rate. (a) Failure rate vs rated value (b) Failure rate vs number of tests.

design and testing need to be combined for optimization. From the viewpoint of design, the derating design is not cost effective because it increases the development costs. When testing to validate a reliability requirement is also considered, however, the derating design may be cost effective if the decrease in cost from testing is larger than the increase in cost from design. For example, suppose that two points *A* and *C* in Fig. 1(a) have failure rates that decrease with the number of tests as shown in Fig. 1(b). When the failure rate requirement is given by λ^*, the numbers of tests performed are denoted by n_A and n_C, respectively. If the derating design improves the reliability, then we have $n_C < n_A$. Even a small difference between n_A and n_C may cancel out the increased design cost especially if the unit test is very expensive. The reduction in cost depends on the derating level and the behavior of the failure rate during test. At present, there is no model available for quantifying the effect of derating design on the development cost which incorporates both the design cost and the testing cost.

The purpose of this paper is to present an approach that quantifies the effect of derating design on the cost and the reliability from which the optimal derating level is determined. The paper is organized as follows. Section 2 describes the proposed model. In the first part, the reliability is expressed in terms of the derating level under the assumption that the nominal failure rate of the item is constant with time for a given rated design value. The second part begins with the development cost, which is expressed by the rated design value and the number of tests. The development cost is modified to incorporate the design uprating and the test derating. In the third part, the optimal derating level is obtained to maximize the reliability or to minimize the development cost that satisfies a fixed reliability requirement. Section 3 presents the application of the proposed model to the design of liquid rocket engines as an example. Finally, the conclusions are given in Section 4.

2. Model

Suppose that an item is required to withstand a certain stress level of $S(1)$ in field operation. Consider a derating design where the item is rated at $S(\alpha)$ where $S(\alpha) = S(1)/\alpha$ for operation at 100 α% of its rated value when $0 < \alpha \le 1$. Such a design has a derating level of $1-\alpha$. When α is unity and thus the derating level is given by zero, the derating design is reduced to the ordinary design where the item is rated at $S(1)$ to be operated at its rated value. In the following, we present a model to quantify the effect of derating level on reliability and cost.

2.1. Reliability

Let an item have an exponential lifetime distribution for a fixed stress level. The exponential distribution is widely used especially in the early design stage to investigate the trade-off between different design options because it has only one parameter, called the failure rate. However, the proposed approach is not limited to a constant failure rate, so the failure rate can be more generally assumed to be a function of time. Let $\lambda(S(\alpha),\alpha)$ be the failure rate of an item that is rated at $S(\alpha)$ in the design stage and operated in field at 100α% of its rated value. Thus, $\lambda(S(1),1)$ and $\lambda(S(\alpha),1)$ represent the nominal failure rate in the ordinary and the derating designs, respectively, which are denoted in Fig. 1 by *A* and *B*. In the following, we explain a procedure to relate $\lambda(S(\alpha),\alpha)$ and $\lambda(S(1),1)$.

Let $K_1(\alpha)$ be a factor to scale the nominal failure rate for considering the design uprating. Suppose that the nominal failure rates for two rated design values of S_i and S_j have the following power law [19,20,27]:

$$\lambda(S_i,1) = \lambda(S_j,1)\left(\frac{S_i}{S_j}\right)^w, \quad w > 0. \tag{1}$$

It follows from Eq. (1) that

$$K_1(\alpha) = \frac{\lambda(S(\alpha),1)}{\lambda(S(1),1)} = \left(\frac{1}{\alpha}\right)^w, \quad w > 0, \;\; 0 < \alpha \le 1, \tag{2}$$

where w is the exponent of the design uprating for the nominal failure rate. If α=0.5, then an item is rated 50% higher in the design and its nominal failure rate is increased by 2^w. For any fixed $w > 0$, $K_1(\alpha)$ decreases with α. When α is unity, $K_1(\alpha)$ is minimized. A large value of w implies the fast growth in the failure rate as the rated design value increases. For example, thrust is rated in the early design stage of a liquid rocket engine to produce a certain amount of force for moving the rocket through the air at a fixed operating condition. While advanced aerospace countries suggest w=0.1017 [19], a larger value of w may be selected by other countries less able to increase thrust. For a fixed α, the benefit of derating design decreases in w since $K_1(\alpha)$ increases with w.

The item developed in the derating design is operated in field at 100α% of its rated value. Due to the operational derating, the item failure rate in field operation, $\lambda(S(\alpha),\alpha)$, is smaller than the nominal failure rate, $\lambda(S(\alpha),1)$. Let $K_2(\alpha)$ be a factor to scale the nominal failure rate for considering the operational derating. Thus, we define

$$K_2(\alpha) = \frac{\lambda(S(\alpha),\alpha)}{\lambda(S(\alpha),1)}, \quad 0 < \alpha \le 1, \tag{3}$$

which denotes the fraction of the nominal failure rate that remains after derating. By definition, $K_2(\alpha)$ must increase with α and $K_2(\alpha)$ reaches its maximum when α is unity. When reliability data are

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