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Performance-Based Reliability Measures for Gracely Degrading Systems: the Concept
성능이 서서히 저하되는 시스템의 신뢰도 척도

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ABSTRACT

In the performance domain, physical performance is a measure that represents some degree of system, subsystem, component or device success in a continuous sense, as opposed to a classical binomial sense (success or failure). If applicable sensing and monitoring means exist, physical performance can be observed over time, along with explanatory variables or covariables. Performance-based reliability represents the probability that performance will remain satisfactory over a finite period of time or usage cycles in the future when a performance critical limit (which represents an appropriate definition of failure in terms of performance) is set at a fixed level, based on application requirements.

In the case of inadequate knowledge of the failure mechanics, this physical based empirical modeling concept along with performance degradation knowledge can serve as an important analysis tool in reliability work in product and process improvement.

1. INTRODUCTION

The purpose of the study and practice of reliability is twofold:

1. To help assure component, subsystem and/or system performance in the design, development, manufacture, deployment and support phases and
2. To allow for the prediction of component, subsystem and/or system reliability performance.

Reliability is classically thought of in a binomial sense (success/failure) and performance is thought of in a continuous sense (power output, thrust, torque and so forth). The classical approach to the prediction of reliability is based on the numerical values of the recorded operating times to failure of the system/component under consideration. Hence, traditional reliability is posterial because it can be determined only after failure has occurred [8,12].

Our present day abilities to monitor, measure and model allow us the opportunity to predict the prospect of system, subsystem, device, or equipment performance directly from on-line performance information when such system's performance is degrading gracely rather than catastrophic failure in nature. One can quite naturally relate concepts of reliability and classes of degraded performance. This concept enables us to envisage the reliability to a conditional indicator which activates an alarm whenever the level of degraded performance "drops" too far. The use of such indicators complies with the requirements of on-line failure diagnosis and may lead to a notable increase in the safety and availability of the equipment to which they are connected through continuous performance monitoring [3,9].

The objective of this paper is to develope the performance-based reliability measures in the performance domain that uses on-line performance information and provide the concept necessary to implement the procedure.

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2. CONCEPT OF PERFORMANCE-BASED RELIABILITY

The conceptual notion of performance-based reliability is very appealing and tied directly to physical performance. Figure 1 shows individual performance curves for each of 8 devices tested or monitored. These curves show performance dropping off as a function of time, at a given load (the slice taken).

A performance plane is drawn at a low performance level in Figure 1. The points at which these performance curves pass through this plane are equivalent to failure times (life times) that would be recorded in a classical reliability study. The classical practice has been to take these failure times and fit them to parametric models, such as a Weibull model, and then use this model as a reliability predictor. In order to add further detail to this hypothetical illustration, one can think about passing a plane in a vertical direction through a point on the time axis. This intersection is shown in Figure 1. In Figure 1, the vertical plane represents a censoring plane. Placement of the censoring plane at a preselected point in time would be known as a Type I or time censoring concept in classical reliability work. If this same plane were passed through the jth ordered failure time, it could be referred to as a Type II or failure censoring concept [2,5]. In relation to performance degrading systems, we are concerned with developing the conditional probability (reliability) that the performance will be above (below) the performance plane for the amount of time stated, under a given set of operating conditions.

3. DEFINITION OF PERFORMANCE-BASED RELIABILITY

Usually, physical performance can be measured to some degree with regard to effectiveness of product. Moreover, these measurements represent some relative degree of success that a component, subsystem, or system is experiencing. These performance measures, at any point in time, differ mainly depending on usage level, operating conditions, environmental conditions, and product deterioration. These measurements represent quantitative information which is readily available at any time during the lifetime of a product if a sensing mechanism is available. Performance data collected over time represents a performance history for a product. It is desirable to measure and record explanatory variables along with performance information. This historic profile can be used to make inferences about various reliability measures of a component, product, device, equipment, subsystem, or system.

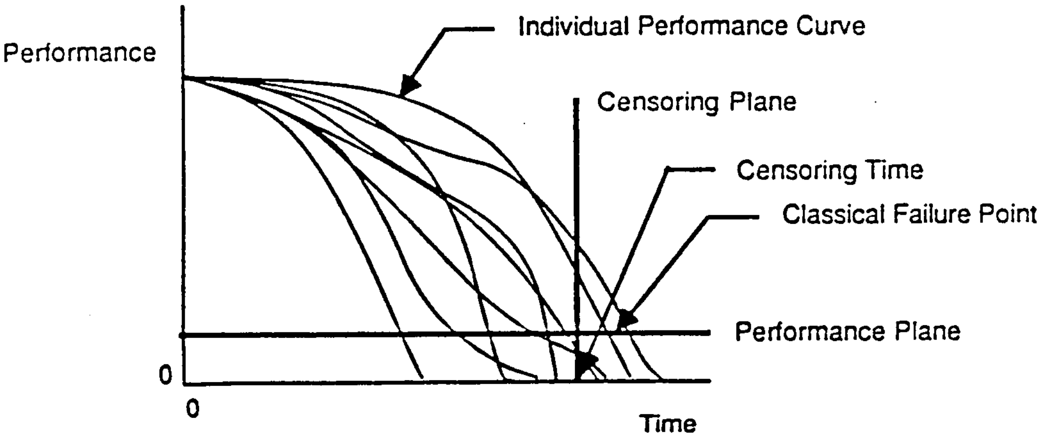


Figure 1: Indivisual Performance Reliability Curves for a Given Load level with a Performance and Censoring Plane Superimposed.

For example, we can incorporate such factors (e.g., performance measures, humidity, temperature, voltage, cumulative operating hours and so forth) into performance-based reliability models. Thus, we may be able to assess the risk associated with the performance over the "failure-free" operating period or a given mission. By analyzing performance data, which can be measured before a product fails, we may be able to assess the effects of such factors on performance degradation. This knowledge may allow us to have a better understanding of a process or product and ultimately improve it or perform preventive maintenance before a failure occurs. Furthermore, we may be able to make an on-line prediction of its probability or degree of success for a given period of time in the future. This information may also enable us to take corrective action if it is necessary.

In this context, performance-based reliability measures utilizes performance information which is very product specific. When an appropriate definition of failure, in terms of performance, is given, performance-based reliability is defined as "the conditional probability that the performance measures of a component, device, equipment, product, subsystem, or system is less (or greater)than a performance critical limit (which represents an appropriate definition of failure in terms of physical performance), given operating and environmental conditions, for a specified period of time or cycles." It can be summarized as

$$P(\text{Performance} < (\text{or} >) \text{ PCL} \mid \text{OCP}=(O_1, O_2,\ldots, O_k), \text{ECP}=(E_1, E_2,\ldots, E_k), T > t), \tag{1}$$

where PCL is the performance critical limit,
OCP is a vector of operating conditions,
ECP is a vector of environmental conditions, and
T is a random variable that represents time to failure.

4. ASSUMPTIONS

As far as physical performance-based reliability is concerned, we are interested in establishing models and data analysis techniques for degrading product performance over time under certain load conditions and under known environmental conditions. Conceptually, this is done by extrapolating performance degradation to predict the time to reach a critical performance plane (failure level). Performance degradation analysis will allow life projections and conditional reliability predictions. These projections and predictions can serve as valuable information for decision making, as to future action such as tool replacement in a computer-aided manufacturing environment. In order to develop these mathematical or probabilistic relationships, assumptions are necessary. Assumptions underlying performance models are described below [6]:

1. Performance measures may drift up and down, but must ultimately decrease or increase. That is performance degradation is, in the long run, not reversible.
2. A model usually applies to a single degradation process (mechanism or failure mode).
3. Degradation of product performance before service starts is negligible.
4. Performance can be measured with a limited amount of random error (the performance signal is detectable, even though noise in the measurement exists).

5. PERFORMANCE-TRACKING MODEL AND RELIABILITY MEASURES

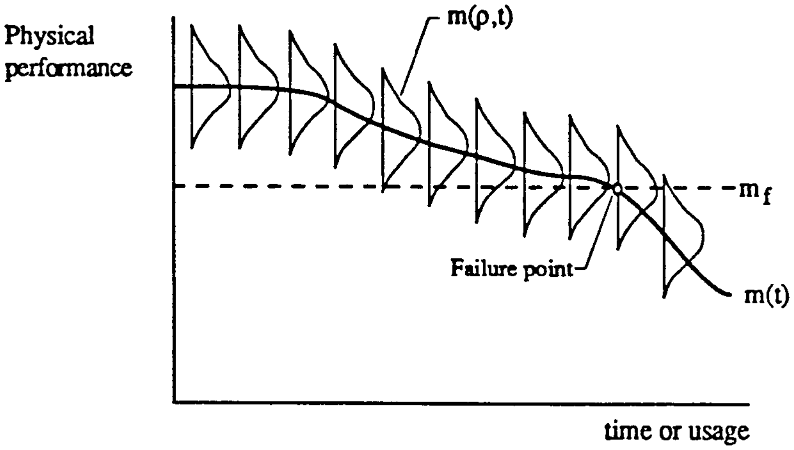
Let m(t) represent a trace of expected performance, measured in whatever physical units are appropriate. Define a critical performance level, m_f, below which a failure is said to exist and above which a success is said to exist. Each m(t) indexes a performance distribution with dispersion σ^2. Let $m(\rho, t)$ represent the performance distribution. The relative degradation intensity can be expressed as

$$P\{m(\rho,t) < m_f\} = \int_{-\infty}^{m_f} m(\rho,t)\,d\rho, \quad m(t) > m_f \tag{2}$$

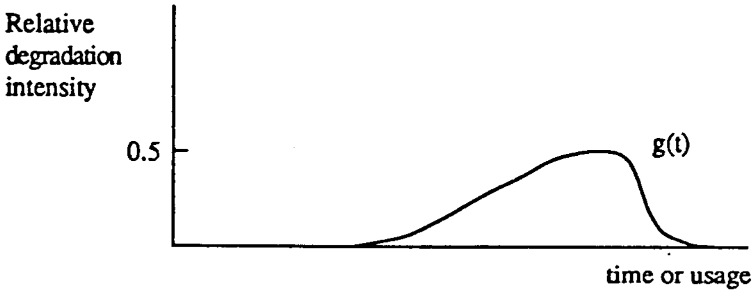
$$P\{m(\rho,t) > m_f\} = \int_{m_f}^{-\infty} m(\rho,t)\,d\rho, \quad m(t) < m_f \tag{3}$$

Now, define the relative degradation intensity trace, Figure 2b, as g(t). The normalized, probability density traced out as m(t) degrades through the m_f plane can be calculated as

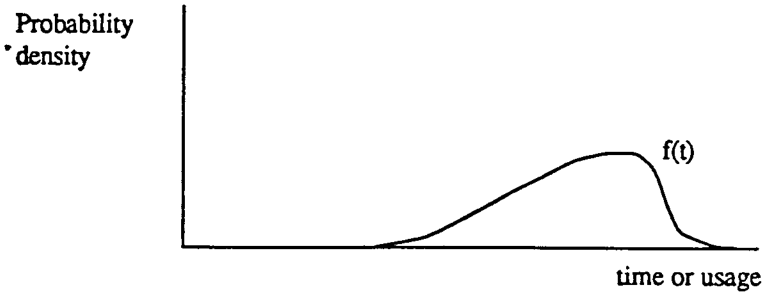
$$f(t) = g(t) \,/ \int_0^{\infty} g(\xi)\,d\xi, \quad t \geq 0 \tag{4}$$



a. Higher is better performance response plot.



b. Performance degradation intensity plot.



c. Normalized probability density function plot.

Figure 2: Performance-based Reliability Concept

Once the f(t) is developed, the cumulative failure density, F(t), and the reliability, R(t), follow directly from

$$F(t) = \int_0^t f(\xi)\,d\xi, \qquad t \geq 0 \tag{5}$$

$$R(t) = 1 - F(t), \qquad t \geq 0 \tag{6}$$

Also, the instantaneous failure rate or hazard rate can be developed from the relationship

$$\lambda(t) = f(t) / R(t) \tag{7}$$

Conditional reliability calculations can be made both a priori and in a real-time environment. In an a pripori sense, classical conditional reliability probability of survival to time , given survival up to time can be computed as

$$R(t_2 \mid t_1) = R(t_2) / R(t_1), \qquad t_2 > t_1 > 0 \tag{8}$$

To construct the performance-tracking function (both m(t) and m(ρ,t)), performance data fitting can be accomplished using standard regression analysis techniques. In the regression process, one can utilize covariates, relating performance to environmental stresses such as temperature, vibration, and so forth, as well as design and application configurations. Hence, response surface technology and experimental design, including robust design techniques, can be readily incoporated into the reliability and improvement process.

6. CONCLUSIONS

The arguments above demonstrate that performance data can be readily measured and translated into a reliability measure. Dealing with physical performance is more attractive to the practitioner. It has advantages over classical reliability measures in the time domain:

1. It can be measured and analyzed before failures occur.
2. It is a continuous measure rather than a binomial event measure, and hence is more informative.

However, these advantages can be realized only if one has a suitable model for the extrapolation of performance degradation and an appropriate definition of the failure point in terms of performance rather than time.

Here, we are concerned with establishing and using relationships between performance, usage level and other explanatory variables. Due to the random effects involved in product performance and its measurement, performance-tracking models should be represented by models involving statistical distributions of performance around typical standard (median or mean) values.

In the case of inadequate knowledge of the failure mechanics, this form of empirical modeling and the engineering relationships for performance degradation can serve as an important analysis tool in reliability work. Once a performance model is established, most classical reliability measures can be extracted from the performance-tracking model. These continuous measurement based models can be developed readily, but require computational effort, due to large amounts of data (when compared to fieldreliability failure time data).

Performance data are continuous so that we can use traditional response surface (regression) statistical methods without modification. While reliability data with censored information require more sophisticated techniques.

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