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A non-linear fuzzy regression for estimating reliability in a degradation process

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ABSTRACT

Since some assumptions such as the function $\phi(\cdot)$ needs to be completely specified and the relationship between μ and $\phi(s)$ must have linear behavior in the model $\mu = a + b\phi(S)$ used in the accelerated life testing analysis, generally do not hold; the estimation of stress level contains uncertainty. In this paper, we propose to use a non-linear fuzzy regression model for performing the extrapolation process and adapting the fuzzy probability theory to the classical reliability including uncertainty and process experience for obtaining fuzzy reliability of a component. Results show, that the proposed model has the ability to estimate reliability when the mentioned assumptions are violated and uncertainty is implicit; so that the classical models are unreliable.

1. Introduction

In accelerated life testing, the test units are subjected to more severe stresses than those of the normal operating conditions, to shorten the testing time and to get more failures. The estimation of the normal stress level of the process factors based on the accelerated life testing data is performed by an extrapolation process [31]. Three particular acceleration equations that have been commonly used for the extrapolation are the power law model, the Arrhenius model and the Eyring model [20,39]. These models have the common linear structure $\mu = a + b\phi(S)$, where $\phi(.)$ is a pre-specified function, a and b are coefficients that need to be estimated. This model is based on two assumptions: the function $\phi(.)$ needs to be completely specified and the relationship between μ and $\phi(S)$ must be linear. If one of these assumptions is violated, then results from extrapolation procedure will not be reliable. As the estimated reliability depends on the extrapolation model, it also will not be reliable.

As it is well known, the natural way to degradation is non-linear, since the loss of material at each moment in the time is not proportional. Moreover, if the mechanism of the application is not fully understood, in such form that the appropriate extrapolation model could be completely specified, our results could be biased [33]. It is possible to use a no-linear model to performance the process; however, it contains uncertainty which is not considered by these kinds of models. Therefore, since the information related to the failure of a component, obtained by means of extrapolation process are estimated and are not observed, it is necessary to model the uncertainty as well as the way to degradation of the component. In this case, we could use other tools like fuzzy logic systems, fuzzy regression and fuzzy numbers to model no-linear systems and to make the extrapolation process including the uncertainty.

Fuzzy logic systems represent an attractive tool to aid the research, when the precise measurement of model is limited [14], it is because these kind of systems let us to model the spatial variability. For example [37], focused on the prediction of the initiation time for corrosion and/or the estimation of the residual strength of structures. They have pointed out the necessity of modeling the spatial variability of the model parameters in order to be able to characterize, not only the probability of degradation, but also the extent of damage. Since this extent of damage is the natural variable that characterizes the global state of damage of the structure, in this case, it could be used for optimizing maintenance policies.

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The present paper intents to generate a policy to model degradation process and involve the use of fuzzy sets. Several papers have been proposed, however related works are considered only the use of qualitative information (by means of linguistic variables), as the principal motivation for using fuzzy logic.

Shi et al. [35] used opinions from experts to collect information about the importance of the indicators and preference about the alternatives, a fuzzy multi-attribute decision-making method was designed to assess and prioritizing projects of ecological revetment for slope protection. Li [21] showed the modeling of periodic preventive maintenance policies of a system and its parameter estimation of failure distribution and restoration effects on the degradation rate. A fuzzy system was built by using a Particle swarm optimization based method. The performance of the fuzzy system was used as a fitness function to guide the search in Particle swarm optimization. Marano et al. [23] proposed a reliability of reinforced concrete structures where an efficient alternative approach was made by considering fuzzy time-dependent reliability analysis. Sharma et al. [34] proposed the combination of qualitative and quantitative techniques for risk and reliability analysis of a paper mill where fuzzy synthesis of failure and repair data using fuzzy arithmetic's had been used. A new intelligent system for detecting the occurrence of a fault in machinery in real time was proposed by Wang [44], this approach uses a monitory reliability by integrating the predicted machinery conditioned to fault diagnosis. Karbhari et al. [15] used the Arrhenius method and the procedure developed by Phani and Bose [32] for modeling mechanisms and processes of deterioration, also for estimating their rates.

On the other hand, fuzzy regression methodology has been used to model processes with fuzziness and limited experimental data sets. Chan et al. [7] proposed a genetic programming based fuzzy regression for modeling manufacturing processes with behaviors that do often carry interactions among variables or higher order terms. A fuzzy linear regression algorithm was used to estimate the contributions and the fuzziness of each branch of the tree, in order to determine the fuzzy parameters of the genetic programming based fuzzy regression model. Tanaka and Lee [38] made an exponential possibility regression analysis by an identification method. They selected the minimum number of coefficient vectors which represent all the given data. Then they applied identification method to determine a possibility distribution of coefficients in the fuzzy linear system. As it was mentioned, the extrapolation process is not linear due to the natural way of degradation, so that these methods are not applicable to the extrapolation process; however they represent a way to address the problem. Mosleh et al. [28] developed a hybrid method based on fuzzy neural network for approximating fuzzy coefficients of fuzzy polynomial regression models with fuzzy output and crisp inputs. They proposed an algorithm from the cost function of the fuzzy neural network. Bargiela et al. [3] presented an iterative algorithm for multiple regression models with fuzzy variables; they posed the regression problem as a gradient-descent optimization. Abdalla and Buckley [1] applied a fuzzy Monte Carlo method to certain fuzzy non-linear regression problems for estimating the best solution of triangular fuzzy numbers, for the fuzzy coefficients in the model. They used a quasi-random number generator to produce random sequences of the fuzzy vectors which uniformly fill the search space; their method obtained solutions as well as evolutionary algorithm. It is worth to mention that, in this work, the non-linear model needed to represent the way of degradation; it does not need any simulation because the data is obtained by means of accelerated life testing, so it is necessary to model real data taken from a degradation process; so that, it is convenient to use triangular fuzzy numbers instead of random data. D'Urso et al. [11] proposed a robust fuzzy linear regression model based on the least median squares-weighted least squares estimation procedure, for data contaminated by outliers. They also defined suitable goodness of fit indices to evaluate the performances of the model.

In order to estimate the reliability of a component is necessary to observe a sample conformed by times to failure related of the component in study. Moreover, the classical reliability theory assume that there is some complete probabilistic information about the system or component reliability behavior, that is, two conditions must be fulfilled: (1) all probability distributions are perfectly determinable and (2) the system components are independent. If at least one of these conditions is violated, only an interval reliability measure can be obtained [41]. The fuzzy sets and possibility theory are often used in reliability analysis as an alternative to the classical probability theory; fuzzy reliability models can be viewed as an interesting class of models for taking incompleteness of information into account, with a variety of challenging open research problems. In the present case, these kind of models are useful because times to failure used to determine the reliability of the component are estimated and are not observed, so that, they contains uncertainty. The uncertainty is closely connected with the concept of information. The most fundamental aspect of this connection is that uncertainty is a result of some information deficiency pertaining to the system within which the situation is conceptualized [18]. Then, for including the uncertainty in the reliability model, the theory of imprecise probabilities [42] and its analogs: the theory of interval statistical models [19] and the theory of interval probability [45] can be used, which represent a general and promising tool for reliability analysis. For example [6] mentions some applications of the fuzzy methodology in system failure engineering traced back to Kaufmann's [16] work. An interesting application related to the present work is fuzzy methodology in mechanical/structural reliability; where a system failure occurs as the system stress (load) exceeds the system strength (resistance); the failure criterion and the system load should be fuzzy, of course, the system behavior can be fuzzy too.

Considering the related works, in this paper we propose to use a non-linear fuzzy regression model (Section 4) to performance the extrapolation process, in order to include uncertainty in the estimated times to failure of a component analyzed by a degradation process. Therefore, since the times to failure are fuzzy numbers, it was adapted the fuzzy probability theory (Section 3) to the classical reliability analysis (Section 2) for estimating the fuzzy reliability of a component (Section 6). Finally, the method was applied to the data published by Gonzalez et al. [13] in order to test the ability of the proposed method. The principal aim of this paper is to show that is possible to make an accelerated life test analysis including uncertainty and process experience by means of a fuzzy theory.

2. Reliability engineering

A critical factor of productivity in an industry is the maintenance of its installations, so it is necessary to continually improve its performance. In order to develop an effective maintenance program, an extensive knowledge about the reliability and maintainability is needed. This knowledge is implicit on the reliability engineering, which provides the theoretical and practical tools through which the probability and capacity of parts, components, equipment, products and systems fulfill their required functions in determined periods of time without failures, in specific environments and with a desired confidence that can be specified, designed, predicted, proven and demonstrated [29]. An important tool of reliability engineering for determining the reliability indicators used in the development of maintenance plans is the analysis that uses parametric models of probability which may be represented by means of probability distribution functions. The probability distribution function $F(x)$ represents the results which are obtained in a