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Hybrid genetic algorithms for structural reliability analysis

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Abstract

The traditional genetic algorithms (GA) involve step-by-step numerical iterations for searching the minimum reliability index of a structural system, and therefore require a relatively long computation time. In practice the size of a design problem can be very large, the limit state functions are usually implicit in terms of the random variables. When using the traditional genetic algorithms, one can encounter problems with the immense effort required in coding ones own finite element code (or for integration with other commercial finite element software) when using the traditional genetic algorithms. For convenient practical applications of the GA in engineering, two new GA methods, namely, a hybrid GA method consisting of artificial neural network (ANN) and a hybrid GA method consisting of ANN and Monte Carlo simulation with importance sampling are proposed in the present study. A distinctive feature of these proposed methods is the introduction of an explicit approximate limit state function. The explicit formulation of the approximate limit state function is derived by using the parameters of the ANN model. By introducing the derived approximate limit state function, the failure probability can be easily calculated, practically when the limit state functions are not explicitly known. These proposed methods are investigated and their accuracy and efficiency are demonstrated using numerical examples. Finally, some important parameters in these proposed methods are also discussed.

Keywords: Genetic algorithms; Artificial neural network; Monte Carlo simulation with importance sampling; Reliability method; Failure probability; Limit state function

1. Introduction

During the last two decades much effort has been directed towards reliable and efficient methods for reliability analysis of structures. Among these methods, first-order and second-order reliability methods (FORM and SORM) and Monte Carlo simulation (MCS) methods are the earliest and most widely used methods in the structural reliability analysis.

FORM and SORM are based on first-order or second-order approximations of the limit state at the design point. Extensive reviews of these methods are found in [1–3]. These methods require the evaluation of the derivatives of limit state functions with respect to the random variables. When these functions are explicit functions of the random variables, it is easy to compute the derivatives of these functions. However, in many cases of practical importance, particularly for complicated structures, the limit state functions are usually implicit in terms of the random variables. Therefore, derivatives of the limit state functions are not readily available. Moreover, a significant disadvantage of these methods is that they may lead to erroneous results when the limit state function has multiple local minimal distance points [4].

MCS uses randomly generated samples of the input variables for each deterministic analysis, records the numbers of times that failure occurs, and estimates probability of failure after numerous repetitions of the deterministic analysis. This method is robust, simple and easy to use. Therefore, the method is often used to validate other analysis techniques. However, the method has one drawback: it needs an enormously large amount of computation time. To reduce the computational cost, different variance reduc-

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tion techniques such as importance sampling [5,6] and adaptive sampling [7] can be employed.

In this paper, we investigate another route for structural reliability, genetic algorithms (GA). The genetic algorithms calculate the probability of failure by using the genetic search technique based on a natural selection process and following a search path until failure is reached. Compared with FORM/SORM, the genetic algorithm has advantages that it does not involve the difficulties of computing the derivatives of limit state functions with respect to the random variables and has the capability of identifying global optimum values of the limit state function. On the other hand, when FORM and SORM methods encounter difficulties, the genetic methods can be employed to obtain/improve results with a reasonable amount of computational cost compared to MCS method. Not so many attempts are reported about the reliability analysis using the genetic method. A paper by Zhao and Jiang [8] examines the application of the genetic method to the reliability analysis of structures. Shao and Murotsu [9] developed a new selective search procedure combined with a genetic algorithm and demonstrated the capacity of the search procedure in their application to structural reliability analysis. However, one drawback of the GA search algorithm is the excessive number of iterations required for the algorithm to converge. To improve the efficiency of the GA search, Deng et al. [10] proposed a modified GA, referred to as the shredding genetic algorithm (SGA). SGA follows the practice adopted in modern breeding technology where healthy animals are cultivated by interfering with the natural selection process and filtering out pubs with undesirable characteristics using the principle of elitism. By simulating this filtration process, SGA focuses the search around the most important genes thereby improving GA's efficiency. To further improve the efficiency of the SGA, Wang and Ghoson [11] propose an extension algorithm of the SGA by combining the benefits of the shredding and learning operators of Deng et al. [10] to the linkage process developed by Harik and Goldberg [12]. Two improvements are made to the SGA. The first is to include linkage-learning operators to improve the convergence of SGA to the local optima as well as the global optimum. The second is to add an exploiter process to refine the local search process and accurately determine solutions that may not necessarily lie in the directions that were pre-set during the original genetic coding.

The GA algorithms proposed by these authors are valid and have good properties but they do have some shortcomings for practitioner engineers. Examples of these difficulties are:

1. The user has to be acquainted with genetic algorithms in-depth, and it could be difficult to directly utilize already existing finite element software.
2. In some cases, to achieve convergence, the selection of some user-defined parameters such as population size, probabilities of crossover and mutation, and maximum number of generations is crucial. Thus, these algorithms may fail to converge if these parameters are not assessed properly.
3. Sometimes sophisticated search techniques complicate the method, though improve its performance.
4. The genetic algorithms involve step-by-step numerical iterations for searching the minimum reliability index of a structural system, and therefore require a relatively long computation time.
5. The reliability analysis of structures with large number of degrees of freedom using the genetic algorithms will have the huge computational volume and will be very time consuming.

In this paper, we propose a method that uses traditional GA only one time to obtain the reliability index and a simple importance sampling technique to improve the obtained estimate. In this way, the numerical iteration procedure during traditional GA search is unnecessary for the proposed method, thus saving the computation time significantly. Moreover, in practice the size of a design problem can be very large, the limit state functions are usually implicit in terms of the random variables and one can encounter problems with the immense effort required in coding ones own finite element code (or for integration with other commercial finite element software). In the proposed method we utilize an artificial neural network technique (ANN) to solve these problems. It should be pointed out that the concept of integration of the GA and ANN was introduced by Rafiq and Williams [13]. However, to the knowledge of the author, it has not been applied to the structural reliability problems. The present paper makes a contribution in this regard.

The remainder of this paper is structured as follows. Section 2 reviews the key procedures of the traditional GA for reliability analysis. Section 3 presents two new hybrid GA algorithms for reliability analysis. Section 4 demonstrates the validity and efficiency of the proposed methods by some numerical examples. Section 5 discusses some important parameters in the proposed methods. Finally, some conclusions are drawn in Section 6.

2. Genetic algorithms for reliability analysis

A reliability problem can be formulated in the following form:

$$\begin{aligned} &\text{Minimize } \beta = \|\mu\|^2 = \mu^{\mathrm{T}} \cdot \mu \\ &\text{Subject to}: g(\mu) = 0 \end{aligned} \quad (1)$$

where μ is the vector of standard normal variates; $g(\mu)$ is the limit state function; β is the reliability index.

The problem in Eq. (1) is a constrained nonlinear optimization problem. In this paper, the genetic algorithm is used for solving the optimization problem. A genetic algorithm is a search/optimization technique based on the survival of the fittest theory and natural section proposed by