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Enriched self-adjusted performance measure approach for reliability-based design optimization of complex engineering problems

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ABSTRACT

For reliability-based design optimization (RBDO) of practical structural/mechanical problems under highly nonlinear constraints, it is an important characteristic of the performance measure approach (PMA) to show robustness and high convergence rate. In this study, self-adjusted mean value is used in the PMA iterative formula to improve the robustness and efficiency of the RBDO-based PMA for nonlinear engineering problems based on dynamic search direction. A novel merit function is applied to adjust the modified search direction in the enriched self-adjusted mean value (ESMV) method, which can control the instability and value of the step size for highly nonlinear probabilistic constraints in RBDO problems. The convergence performance of the enriched self-adjusted PMA is illustrated using four nonlinear engineering problems. In particular, a complex engineering example of aircraft stiffened panel is used to compare the RBDO results of different reliability methods. The results demonstrate that the proposed self-adjusted steepest descent search direction can improve the computational efficiency and robustness of the PMA compared to existing modified reliability methods for nonlinear RBDO problems.

1. Introduction

With the development of structure design theory and improvement of computation resources, structural design optimization has made great progress. To satisfy the requirements of design optimization under uncertainty, reliability-based design optimization (RBDO) method is developed to execute design optimization and meet the requirement of reliability analysis. Typically, reliability index approach (RIA) [1, 2] and performance measure approach (PMA) [3] are two main RBDO models.

In general, inverse formulation is more suitable for the RBDO problem with high reliability index which cannot be solved by safety index approach [4]. Tu et al. [3] proposed the inverse reliability method for PMA, and pointed out that RIA is more inefficient in the case that design points violate the reliability constraints, while PMA is inherently robust to solve RBDO problems with high efficiency. Inspired by the idea of PMA, Lee et al. [5] introduced the same procedure into RBDO and proposed target performance-based approach. The comparative analysis of RIA and the PMA shows that the latter is not

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only better in computational efficiency but also has merits of good numerical stability. Furthermore, PMA has well-defined concept, simple solution and high robustness [6], and thus it has been widely used in RBDO problems.

A RBDO problem resolves the issue of reliability-based design but this progress generates new problems, such as high computational burden, numerical instability and inaccurate optimum design conditions. It has been found that a huge computational burden is required to handle the reliability analysis which is indispensable for the reliability constraints feasible check [7]. Although iterative algorithms have been used to generate the design point, complex constraint functions under uncertainty may lead those algorithms easier to incorrect results. To overcome those obstacles and easily apply RBDO to engineering practice, many researchers were devoted to the study of this field and its practical application [8–12]. Compared with traditional nest-loop RBDO method, single-loop strategy [13–15] eliminates the reliability analysis loop to enhance the efficiency. Sequential optimization and reliability assessment method (SORA) [16–19] was proposed to decouple the nest-loop of design optimization and reliability analysis by applying the shift vector into probabilistic constraints to transform the limit state functions. The SORA not only improves the robustness of RBDO process, but also makes it more efficient to handle non-deterministic optimization. Furthermore, Li et al. [20] pointed out that double loop approaches have an excellent numerical stability, but the computational burden is unbearable. By contrast, single loop approaches have a good performance in terms of efficiency, but it is hard to solve highly nonlinear performance measure functions. Youn [21] put forward the adaptive-loop method which involved deterministic design optimization, parallel-loop method and single-loop method into RBDO and possibility-based design optimization problems to enhance the efficiency and robustness of algorithm. Hao et al. [22] established a novel non-probabilistic reliability-based optimization framework, which can provide optimum design for complicated engineering problems without prior knowledge of uncertainty distributions in an efficient and robust manner. Besides, surrogate model is widely used to replace the complex black-box performance functions [23–25]. A framework of multi-objective optimization with interval variables was proposed by Liu et al. [26]. The adaptive surrogate model is used to locate the lowest reliability value within a multi-dimensional interval. A local approximation method using the most probable point (MPP) [27] was proposed to improve the accuracy and efficiency of RBDO methods.

Owing to the simplicity and efficiency, the advanced mean value method (AMV) is widely applied in PMA. However, in previous works [28–31] the iterative sequences of AMV formulation might meet convergence problems in the search process of the minimum performance target point (MPTP), such as the periodic oscillation for some highly nonlinear constraint functions. Therefore, several advanced algorithms such as conjugate mean value method (CMV), hybrid mean value method (HMV) [32], relaxed mean value approach (RMV) [33], hybrid self-adjusted mean value method (SMV) [31], modified mean value method (MMV) [34], step-length adjustment method (SA) [35], were proposed to improve the convergence rate. Yang [36] pointed out that those mean value-based algorithms can improve the numerical stability on account of the prior knowledge and did not give a theoretical explanation about the non-convergence phenomenon. Based on the principle of chaos control, the stability transformation method (STM) was proposed to achieve the convergence control [36–38]. Hence, several chaos control-based algorithms, such as modified chaos control method (MCC) [30], self-adaptive modified chaos control method (SMCC) [39], adaptive chaos control method (ACC) [40], hybrid chaos control method (HCC) [30], enhanced chaos control method (ECC) [22] and adaptive advanced mean value method (AAMV) [41] were employed in RBDO. Compared with mean-value methods, chaos control-based method can adjust the spectral radius of Jacobian matrix for nonlinear limit state function iterative map and stabilize the unstable fixed points. The robustness and efficiency are two important keys to develop the reliability methods for RBDO-based PMA, but the accuracy is also an essential issue to obtain the optimum results with reliability levels. The inverse reliability methods using PMA formula with relatively accurate and stable results as well as efficient computational effort can be interested for successful applications in RBDO problems with highly nonlinear constraints.

In this paper, the self-adjusted mean value method (SMV) is introduced briefly. And then, an enriched self-adjusted performance measure approach is put forward based on the SMV and merit function, which is used to search the MPTP in iterative process with high efficiency and robustness. To certify the efficiency and numerical instability of the proposed enriched SMV method, four complex engineering problems are investigated in this paper, and the performance is compared with those of PMA-based RMV [33], SMCC [39], ACC [40], MMV [34], SA [35] and SMV [31], respectively. Results show that the proposed enriched SMV method has a better performance in terms of efficiency and robustness to solve complex engineering problems.

2. Performance measure approach for RBDO

Traditional deterministic design optimization focuses on searching an optimal design under certain structural behavior constraints. However, RBDO can obtain a more reasonable design by taking uncertainties into consideration, and the deterministic constraints are transformed into probabilistic constraints accordingly. Generally, a RBDO problem is formulated as follows

$$\begin{aligned}
&\text{find} \quad \boldsymbol{d}, \mu_X \\
&\min \quad f(\boldsymbol{d}) \\
&\text{s.t.} \quad \mathrm{P}_f(g_i(\boldsymbol{d}, \boldsymbol{X}) \le 0) \le \Phi(-B_{i,\text{target}}) \qquad i = 1, 2, ..., N \\
&\boldsymbol{d}^L \le \boldsymbol{d} \le \boldsymbol{d}^U
\end{aligned} \tag{1}$$