Reliability-Based Design Optimization of Structural Durability Under Manufacturing Tolerances

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1. Abstract
The objective of this paper is to develop and apply the Reliability-Based Design Optimization (RBDO) process to structural durability in order to obtain a reliable and durable design under given manufacturing tolerances. Since uncertainty propagation to structural fatigue under transient dynamic loading is numerically complicated and computationally expensive, it is challenging to integrate the reliability process into durability optimization. To define durability design constraints efficiently, a preliminary fatigue life analysis is carried out for crack initiation to detect critical spots with short fatigue life. This analysis is used to define the design constraints. A refined durability analysis is then carried out at these critical spots to obtain an accurate measurement of fatigue life. Various model uncertainties such as geometric tolerance and material properties are taken into account to predict uncertainties of the structural durability through advanced reliability analysis. Consequently, the envisioned CAD-based process is developed by integrating the proposed, effective RBDO method with a systematic durability analysis, with emphasis on numerical efficiency and accuracy.

2. Keywords: Reliability-Based Design Optimization (RBDO), Durability Analysis, Performance Measure Approach (PMA), and Hybrid Mean Value (HMV) Method.

3. Introduction
Transient dynamic loadings applied during the service life of a mechanical system leads to structural fatigue that is the primary design concern in terms of safety and durability. Uncertainties in the dimensions and material properties of a structural component due to manufacturing tolerances cause indeterministic nature of fatigue life of a structural component. A probabilistic design approach to structural durability and safety that takes various uncertainties into account provides a reliable design with a required fatigue life span. The objective of this paper is to develop and apply the RBDO process for structural durability to obtain a reliable and durable design under manufacturing constraints, formulated as [1-2]

\[
\text{minimize } \text{Cost}(\mathbf{d}) \quad \text{subject to } P(G_i(\mathbf{d}^X)) \geq 0, \quad \Phi(-\beta_i) \leq \xi, \quad i = 1, 2, \ldots, np
\]

where \( \mathbf{d} = \{d_i\} = \mu(\mathbf{X}) \in \mathbb{R}^n \) is the design vector, \( \mathbf{X} = \{X_i\} \in \mathbb{R}^n \) is the random vector, and \( n, nr, \) and \( np \) are the number of design parameters, random parameters, and probabilistic constraints, respectively. The probabilistic constraints are described by the performance function \( G_i(\mathbf{d}(\mathbf{X})) \), where \( G_i(\mathbf{X}) \geq 0 \) is a failure, their prescribed confidence level \( \beta_i \), and their probabilistic models.

It has been shown in Refs. 1 and 2 that PMA using HMV method enhances numerical efficiency and stability in the RBDO process. However, it is still difficult to use the RBDO process for large-scale industrial applications due to a significant effort required when evaluating probabilistic constraints. In this paper, an M1A1 tank is employed to demonstrate the effectiveness of the RBDO process for durability analysis subject to various uncertainties. The method presented in Ref. 3 is used for efficient RBDO.

4. Reliability-Based Design Optimization for Durability Analysis [3,4]
In design optimization for fatigue life, the number of design constraints could be very large if a fatigue life constraint is defined for every point of the structural component. To make the problem computationally tractable in structural durability analysis, a preliminary fatigue life analysis for a crack initiation is carried out in Fig. 1(a) to detect those critical spots with a short fatigue life and to define the design constraints. Refined durability analysis is then carried out at these critical spots to accurately predict fatigue life. The design constraints for durability in Eq. (1) are defined as

\[
G_i(\mathbf{d}(\mathbf{X})) = 1 - L_i(\mathbf{d}(\mathbf{X}))/L_t
\]

where \( L_i(\mathbf{d}(\mathbf{X})) \) is the crack initiation fatigue life at a current design, and target fatigue life \( L_t \) is set to 8 years. In this process, durability and reliability analysis workspace (DRAW) [3] predicts the crack initiation fatigue life, which is

Uncertainties in geometric tolerance and material properties are considered as model uncertainty in the probabilistic durability model. Uncertainties of geometric tolerance and material property are modeled with a 10% and 3% coefficient of variation (COV), respectively. Eight shape design and random parameters are illustrated in Fig. 1(b) and six fatigue material parameters for the fatigue crack initiation are summarized in Table 1 [4].

Table 1. Fatigue Material Property of SAE 4340 Steel, SI Unit

<table>
<thead>
<tr>
<th>Cyclic Strength Coefficient, $K'$</th>
<th>Cyclic Strength Exponent, $n'$</th>
<th>Fatigue Strength Coefficient, $\sigma'$</th>
<th>Fatigue Strength Exponent, $b$</th>
<th>Fatigue Ductility Coefficient, $\alpha'_f$</th>
<th>Fatigue Ductility Exponent, $c$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.358×10^9</td>
<td>0.12</td>
<td>1.220×10^9</td>
<td>-0.073</td>
<td>0.41</td>
<td>-0.60</td>
</tr>
</tbody>
</table>

5. An Integration of RBDO Process for Roadarm Durability
The envisioned CAD-based process is developed by integrating a proposed effective RBDO method with systematic durability analysis, with emphasis on numerical efficiency and accuracy.

7. References