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STOCHASTIC MODELING AND SIMULATION FOR LARGE-SIZE COMPUTATIONAL MECHANICS PROBLEMS

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ABSTRACT

The paper discusses the high-performace computing (HPC) methodology solution to complex computational stochastic mechanics problems for complex mechanical system reliability predictions. The presented integrated HPC reliability computational framework efficiently combines physics-based stochastic computer models with real-life evidence coming from experimental tests and field observations. The major constituents of the new reliability software are state-of-the-art refined physics-based prediction models, including a novel HPC stochastic FEA technology that can handle effciently large-size FE models on multiple processors combined with state-of-the-art stochastic modeling and simulation for fast risk predictions using available HPC resources.

The stochastic simulation-based HPC reliability approach for reliability prediction includes a set of new, innovative computational tools that provide great efficiency to the overall HPC implementation. These innovative computational modeling and simulation tools include:

i) Stochastic parallel FE technology that can be used for large-size FE models including innovative stochastic preconditioning schemes via Markov Chain Monte Carlo simulation

ii) Accurate stochastic response approximation and simulation models including three-level hierarchical models (3LHM) and the meshless fast-probability integration (MFPI) models

iii) Efficient MCMC-based technology for including the limited and lack of data effects on reliability prediction

iv) Accurate statistical testing techniques (more accurate than modified or original Anderson-Darling statistical tests) for selecting the most adequate probability distribution in tail regions based on limited data

v) *Physics-based* Bayesian updating scheme based on the parametrization of the local density models (hierarchical models)

The paper shows that each of the above tools has a significant impact on both efficiency and accuracy of reliability predictions. It also shows the effects of combining computer predictions with evidence information form test data using Bayesian updating, and modeling uncertainty due to the limited data on reliability prediction of mechanical systems.

The stochastic parallel FEA technology that was implemented in the in-house SPARTACUS code (Stochastic PARallel Tool for Analysis of Computational Unstructured-meshed Solids) has been developed based on the parallelization of the FEAP finite element code (developed by UC Berkeley) using various HPC numerical libraries from national labs and US universities.

SPARTACUS can handle large stochastic FE model sizes with tens and hundreds on millions of dof on many processors. SPARTACUS's scalability is very good based on a series of comparative studies for various FEA types, FE mesh sizes and FE types done for different numbers of processors.

In addition to SPARTACUS, other key ingredients of the integrated HPC reliability technology are the SPARES (Stochastic PArallel REsponse Surface modeling and simulation) and SPARLIFE (Stochastic PARallel LIFE prediction) frameworks. SPARES uses innovative response surface approximation algorithms based on high-order stochastic field models (3LHM and MFPI). These high-order stochastic field models are based on the stochastic input-output vector joint probability density decomposition. Different clustering techniques are used. SPARLIFE uses stochastic stress-dependent cumulative damage models (based on DCA or DDCA models) for crack nucleation and stochastic linear fracture-mechanics crack propagation models (based on Forman model). The crack nucleation models are applied in conjuction with a stochastic strain-life approach. SPARLIFE uses Weibull and Lognormal analytical life models or non-analytical models that are fitted on simulated results. Bayesian updating and lack of simulation data effects can be introduced in different ways.

SPARTACUS HPC implementation strategy is based on the Controlled Domain Decomposition (CDD) strategy that uses a group of processors with or without dynamic load balancing for performing the stochastic parallel finite-element stress analyses. SPARLIFE HPC implementation strategy is based on the Dynamic Task Allocation (DTA) strategy that uses a typical server-client interactive model for performing the stochastic life prediction analyses.

For performing Reliability Based Design Optimization (RBDO) analyses, the TAO code (Toolkit for Advanced Optimization) developed by Argonne National Lab was interfaced with SPARTACUS and SPARLIFE files. Using TAO, we performed RBDO analyses using different reliability calculation techniques such as FORM RIA and PMA, FORM PMA with MRSA (mean response surface approximation) and SRSA (stochastic response surface approximation).

The paper illustrates the application of the new integrated HPC reliability prediction technology to air/ground vehicle vibration problems. The paper demonstrates the feasibility of the HPC reliability technology by its application to set of reliability sensitivity studies to identify the critical life-drivers that impact most severely on vehicle reliability. The reliability studies showed the effects of various stochastic variations in operating loading conditions (accidental loading, temporary live load changes), manufacturing deviation effects (wall thickness variations, joint stiffness variations, spring damper properties), local plasticity effects on critical location stresses, multiple progressive damage interaction effects (interaction between high-cycle fatigue damage and low-cycle fatigue damages, or corrosion-fatigue damage effects).

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