Dealing With Variability in Design

Probabilistic Design Methods build understanding of reality's randomness and scatter in modelling,

Dr Andreas Vlahinos Advanced Engineering Solutions

Thanks to the development of probabilistic design methods, the definition of a robust design is changing. Until recently, a design was considered robust if all the variables that affected its life had been accounted for and "brought under control." The meaning of robustness is shifting, however, to a measurement of the product design's insensitivity to those variables.

In more concrete, businesslike terms, a robust design is one that meets customer expectations at an affordable cost regardless of customer usage, degradation over the life of the product, and variations in its manufacturing, suppliers, distribution, delivery and installation. All of these can exhibit a high degree of randomness and scatter.

The key difference is how randomness and scatter are handled in the analyses. Designers and engineers have traditionally handled them with safety factors. Some safety factors are derived from observation and analysis (empirical) but many are pure guesswork. In those cases, the bigger the guess, the bigger the risk, the bigger the safety factor - and the more the product is overdesigned.

This portends a revolution in the strategies by which new products are designed. According to Dr. Andreas Vlahinos, described by his peers as a "passionate knowledge worker" and principal of Advanced Engineering Solutions LLC (AES), Castle Rock, Colorado, there are two major drivers for new design strategies:

- Safety factors cannot, of themselves, guarantee satisfactory performance and they do not provide sufficient information to achieve optimal use of available resources.

- The increasing use of optimization tools in engineering designs generates products that are very close to design constraint limits. When this is the case, there is precious little room for tolerances in modeling uncertainties and manufacturing imperfections.*

"A wisely applied Six-Sigma strategy can measure, analyze, improve and control quality issues," Dr. Vlahinos pointed out. *"However, Six-Sigma methodologies have been implemented in management and manufacturing to fix problems. By designing for Six-Sigma quality levels early in the design process, we 'make it right the first time;' therefore we eliminate the creation of problems.*

In short, it is time for designers and engineering management to move into the Brave New World of probabilistic design. Until recently, *"the probabilistic design process was not widely used because it has been intimidating and tedious due to its complexity,"* Dr. Vlahinos explained. *"Successful organisations realise that probabilistic design techniques have enormous positive impact on reducing product costs. This becomes obvious when the total product cost is considered to include the costs of poor quality (rework, product recalls, field service, warranty payments, guarantee costs, missed sales goals, lost customers, liability, etc.)."*

Computers and analysis software also posed problems until recently. Probabilistic design requires a finite-element model to be run many times with varying values to account for the uncertain input parameters. So, before the advent of fast computers and more efficient, user-friendly software a probabilistic analysis was prohibitively time consuming and expensive. Traditional deterministic approaches were faster and cheaper. This has changed in recent years with major advances in analysis software, surges in computer processing speeds and big jumps in addressable memory.

In the more advanced areas of product design, this is changing rapidly due to significant gains in the capabilities of design optimisation and verification software such as capabilities in the Probabilistic Design System (PDS) from ANSYS Inc. PDS has been available for a number of years; more than 100 companies worldwide are using it.

The Challenges

"The ANSYS PDS approach makes probabilistic analysis simple to set up if the control and noise parameters are identifiable," Dr. Vlahinos noted. *"Control parameters,"* he explained, *"are those factors the designer can control such as geometric design variables, material selection, design configurations, manufacturing process settings and so on.*

"Noise parameters on the other hand are factors that affect the design's function that are beyond the control of the designer or too expensive to control or change,"

he added. These include variability in material properties, limitations in manufacturing processes, environmental / operating temperatures and humidity, component degradation over time, etc.

In fact, in any well thought-out probabilistic analysis, these noise parameters actually drive the finalized design solution.

Dr. Vlahinos believes that engineers and designers have grown too comfortable with a "deterministic" approach, he continued. Borrowed from the behavioural sciences, the term characterises a theory that all occurrences are determined by antecedent causes. And by simple extension, if all those antecedent causes can be quantified, the results can always be predicted. Obviously this appeals to engineers and provides aid and comforts to their managers.

In light of the large percentage of new products that fail (90% fail to find a market niche) this is a huge "if." Randomness and scatter are where technology's reach still exceeds its grasp.

The reason has to do with the most fundamental ways that computers do analysis. Models to be analyzed are expressed with specific numerical values such as physical limits of material properties, the coordinates of the component's design geometry (XYZ), tolerances, loads and the mechanisms by which they are applied, etc.

The results of any analysis, deterministic or otherwise, are only as good as the assumptions and input values the designer chooses to represent the component's expectable real-life conditions. Engineers know that every parameter of an analysis is subjected to scatter and randomness. Every input value is uncertain in some way, in other words. For example:

- Material property values differ inherently from one specimen to the next.

- Geometric properties of components can only be reproduced within certain manufacturing tolerances.

- This also holds true for the loads applied to a finite element model. For example, it is almost impossible to measure heat-transfer coefficients, as even the ANSYS user manual points out. Almost all thermal input parameters used in finite element analyses are inexact and the degree of uncertainty grows sharply at elevated temperatures.

It is neither physically possible nor financially feasible to eliminate the scatter of input parameters completely. Probabilistic design analysis substitutes ranges of values and design-sensitivity analyses for safety factors. This does a better job of representing the real world but there is a cost. Typically several hundred data points are gathered for each of several "noise" parameters, complete with randomness and scatter that must be addressed in the choice of sampling technique.

This lets the messiness of the real world intrude on calculations that had often been quite elegant. Probabilistic analysis methods thus demand that designers understand probability and sampling techniques, not just statistics.

"The goal of this kind of robust design," Dr. Vlahinos pointed out, *"is to reduce the product's variation by reducing its sensitivity to the sources of variation rather than by controlling these sources."* In a nutshell, this is the difference between the probabilistic and deterministic approaches.

On a philosophical plane, probabilistic design methods lay out the shortcomings of traditional design methods in the ways that the uncontrollable "noise" variables are addressed.

- In deterministic analyses, all variables are accorded equal status and treatment whether or not they are under the control of the designer. Probabilistic methods on the other hand use statistically sound random variables to characterize the uncontrollable "noise" parameters.

- In deterministic analyses, all variables are quantified with a number that includes a simple margin of safety based on experience with specific applications. Without mishaps, material substitutions or management-driven cost cutting ("value engineering"), these rules of thumb go unexamined for years, if not decades. Probabilistic methods allow for quantifying those effects and taking them into account in a consistent fashion. As a result, a probabilistic analysis identifies the critical drivers of a design, i.e. those variables that most likely will lead to product malfunctions and/or quality problems. This invaluable information helps avoid any problems already in the design phase.

The Solutions

Three of Dr. Vlahinos' recent projects illustrate how probabilistic methods are applied in widely differing situations. They are steel and composite auto parts and the electro-mechanical components of fuel cells.

Steel Radiator Support

A steel radiator support for a sport utility vehicle (SUV). The goal of this analysis was to ensure six-Sigma quality in the manufacturing of a key automotive structural component. The specific problem addressed was that optimized designs-as this one was-may be so sensitive to design parameters that even small changes in design variables could lead to a significant loss of durability.

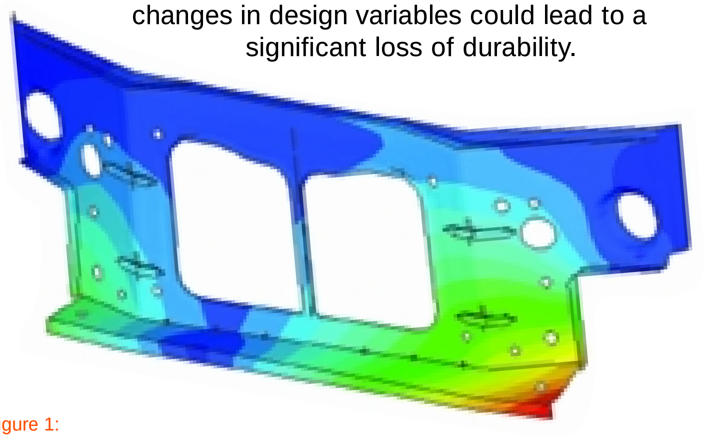

Figure 1:
Parametric determinist model of radiator support

The first major step was identifying the random variables and qualifying their causes. The variations were then assigned mean and standard deviation values. The deterministic constraints were then reformulated as probabilistic constraints with appropriate reliability levels. This was done with two random variables: metal thickness and material yield stress.

This led to a defined performance function calculated in terms of the maximum Von Mises stresses in torsional loading. The result was a reliability curve matching failure probability to material thickness. In this project, Dr. Vlahinos partnered with Dr. Subhash Kelkar, Staff Technical Specialist at Ford Motor Co., Dearborn, Michigan, and presented a well-thought-out Probabilistc Design Techniques approach to ensure Six-Sigma quality. Their technical papers won a best paper award from the Society of Automotive Engineers in 2002.

Fuel Cell Membrane

The effects of uneven pressure distribution on the electro-mechanical fuel cell membrane assemblies. *"In new or emerging industries such as fuel cells, the development time from concept to production is being compressed significantly,"* Dr Vlahinos observed. From an analysis standpoint, *"this means designers must explore a wider than normal range of options and variations in shorter than normal time frames."*

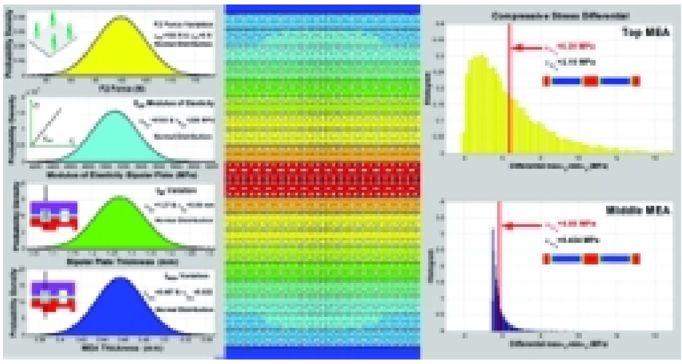

Figure 2: Probabilistic inputs, FEA model and probabilistic outputs of a fuel cell stack

The key parameters in this investigation were the Modulus of Elasticity and Poisson's Ratio of the fuel cell's proton exchange membranes (PEMs), bi-polar plates and end plates. These comprise the fuel cell's membrane exchange assembly, commonly known as the "stack," which is bolted together. Overly tight bolting during assembly reduces the electric conductivity of the assembly (and thus its power and efficiency) and increases its permeability, which hurts service life.

Spacing of the stack's flow and cooling channels and the thickness of the membranes and bi-polar plates were evaluated probabilistically. Using the ANSYS Parametric Description Language (APDL) as a pre- and post-processor, *"the probabilistic design loop was fully automated,"* Dr. Vlahinos said. *"If we view this loop as a transfer function, the mean values and standard deviations for the three design variables (bolt loads) can be considered inputs while the mean and standard deviation of the of the attributes-maximum standard deviation and differential compressive stress-can be considered as outputs."* This is another way of stating that the "noise" parameters drive the design.

These bolt load outputs *"exhibited a high degree of asymmetry in their distribution around their mean,"* Dr. Vlahinos noted. Specifically, analysis showed a 30% higher compressive stresses in the top of the stack than in the middle and the standard deviation was five times larger.

The probabilistic analysis revealed something that a conventional deterministic analysis might have missed. *"Due to the compliance of the 'soft goods' [interspersed in the assembly], the majority of the assembly stack appeared to be insensitive to manufacturing variations,"* he explained. *"Yet manufacturing, material and loading imperfections have a great effect on the stress values of the top assembly"* and thus on the cell's performance.

In this project, Dr. Vlahinos partnered with Kenneth Kelly of NREL and two engineers-Jim D'Aleo and Jim Stathopoulos-from Plug Power Inc., Latham, New York. *"Engineering quality into fuel cell designs is the next step for successful commercialization of fuel cells,"* said Stathopoulos, a Six-Sigma "black belt" and quality systems manager at Plug Power, a leader in fuel cell research, development and manufacturing.

The analysis was further justified by the fact that robust designs are needed if fuel cells are to compete successfully with mature technologies, i.e., internal combustion engines and electricity from the grid. *"Renewable energy and energy efficient technologies cannot afford to plod through the traditional design processes if they are going to compete with mature existing technologies,"* Kelly noted. *"Robust design methods can help new, efficient technologies succeed in the market by reducing the impact of input variations."* Partial funding for all three of these projects came from two DoE units: the FreedomCAR and Vehicle Technology Office and the Hydrogen, Fuel Cells and Infrastructure Technologies Program.

Kelly, who leads the virtual prototyping efforts at NREL's Center for Transportation and Technologies, Kelly observed that, *"the old build-and-test approach is too costly and too time consuming. We need to understand the effect of variation in loads, in material properties and in manufacturing before prototypes are built. The use of CAE modelling tools coupled with probabilistic design, optimisation and Design for Six Sigma (DFSS) techniques will lead to higher quality and more robust designs much sooner."*

Battery Support Tray

Weight reduction in a composite battery support tray, also for an SUV. The goal of this analysis was to determine the sensitivity and the response distribution (stress, stiffness and fatigue life) due to the scatter of the random variables. The scatter of the modulus of elasticity values and the material thickness and stress loading, were defined as probability distribution functions. The response distribution was determined with Monte Carlo and response surface sampling techniques.

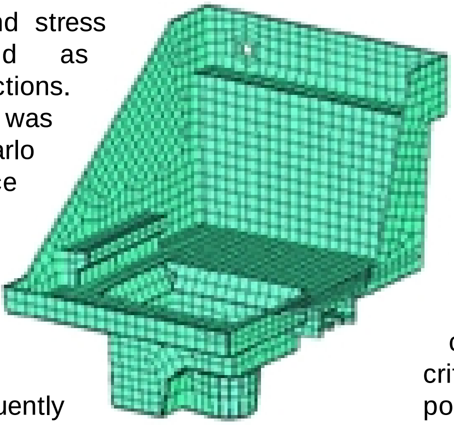

Figure 3: Parametric determinist model of a battery tray

SUV battery trays are frequently over-designed to account for nominal or worst-case scenarios. *"If the scatter in the material properties, thickness and dimensions (manufacturing variations) is accounted for in the finite element analysis stress prediction,"* Dr. Vlahinos pointed out, *"lighter designs will be produced."* In fact, the mean value of the tray's thickness, a Gaussian distribution and a controllable parameter, were treated as an optimization design variable.

"This type of stochastic approach," he continued, *"can be used to investigate the sensitivities of different variables to the objective function and help develop robust designs.* In this project, Dr. Vlahinos also partnered with Dr. Kelkar of Ford Motor Company.

What these three investigations have in common is a methodology (see Figure 4).

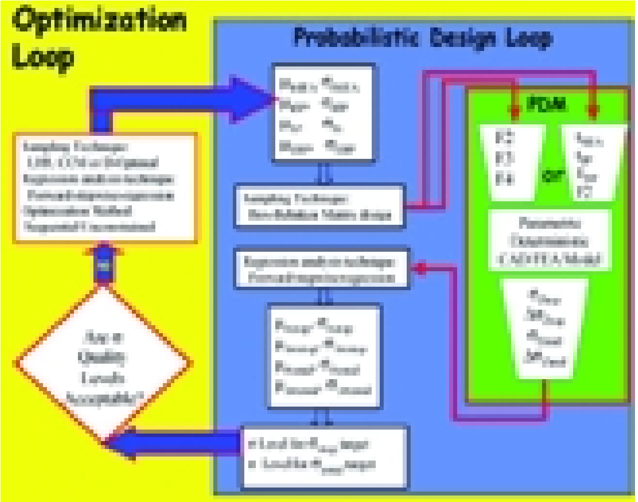

Figure 4. Reusable work flow diagram for robust optimization

The input is the desired quality or qualities of the design. Sound probabilistic methods rely heavily on sampling techniques to generate the maximum stress data used in the analyses. All "noise" parameters are fed through one or more sampling techniques: Monte Carlo, Latin Hypercube Sampling, Central Composite Design and Box-Behnken Matrix. In the form of histograms, probabilistic "noise" range data becomes part of the finite element design geometry in the parametric model.

Then the mean and standard deviation of the response variables (maximum stress, maximum strain) are calculated. Depending on the application, failure probabilities also can be calculated. From them comes the performance criteria required to meet the design qualities as well as pointers to any needed improvements.

Probabilistic sensitivities are among the most important of these pointers. They point unambiguously to the input parameters that are most likely to be the drivers for any malfunctions or quality issues. They also indicate where manufacturing cost could be reduced by using a less costly manufacturing process without impacting quality and reliability.

The probabilistic design analysis, which may be iterated and refined several times, generates approximations of both objective functions and constraints.

At this point the design is optimised to convergence. Performance criteria can include just about any aspect of the design, its specifications, manufacturing and quality assurance processes, or the environment in which it will be used.

The Summary

"The need for innovative tools is apparent now more than ever," Dr. Vlahinos said. *"More complex design requirements and trade-offs are surfacing such as cost, performance, safety, quality, time to market, short life cycles, environmental impacts, WOW aesthetics** and major changes in industries' business models."* In some instances, it is possible that improvement in one area leads to degradation in others.

"The probabilistic approach offers designers greater insight into complex engineering processes that involve statistical variations," he continued. *"This enables the designers to identify better designs that meet the customers' performance objectives and are less sensitive to manufacturing variations."*

From an engineering management standpoint, scatter and variability can also be reduced through better and more precise manufacturing processes or increased efforts in quality assurance, or both. But this means sharply higher costs. As the ANSYS User's Manual puts it: *"Accepting the existence of scatter and dealing with it rather than trying to eliminate it makes products more affordable and production of those products more cost-effective."*

"Uncertainty and scatter in the input parameters of a product is for the most part unavoidable," said Dr. Stefan Reh. Speaking as lead PDS software developer at ANSYS, he observes that *"fighting the inevitable is an abuse of engineering resources that can only be compared to Don Quixote's fight against windmills. As they are doing in these examples, designers should focus on the impacts of those uncertainties on a product performance. Minimizing the impact of uncertainty,"* Dr. Reh continued, *"is what makes products achieve higher quality standards-while becoming more affordable and reliable."*

Probabilistic design methods are among the most effective ways to get a handle on variability in product performance characteristics. These methods are proven tools to help derive measures for improving the quality control of the design and manufacturing processes.

In the absence of probabilistic design, uncertainty and variability lead to products that are over- or under-designed. Both translate into designs with greater risk, not less, and lost revenue.

NOTES

* The bulk of the material in this case history was derived from three technical papers dealing with design analysis of automotive components. They were:

"Effect of Material and Manufacturing Variations on Membrane Electrode Assembly Pressure Distribution" in fuel cell assemblies given at the First International Conference on Fuel Cell Science, Engineering and Technology, Rochester, New York, April 2003. (ASME FUELCELL2003-1707)

"Designing for Six-Sigma Quality with Robust Optimisation Using CAE" delivered at the International Body Engineering Conference & Exposition at the Automotive & Transportation Technology Conference, Paris, France, July 2002 (SAE 2002-01-2017).

"Body-in-White Weight Reduction via Probabilistic Modelling of Manufacturing Variations" delivered at the International Body Engineering Conference & Exposition in Detroit, October 2001 (SAE 2001-01-3044).

For all three papers, Andreas Vlahinos, principal of Advanced Engineering Solutions LLC, Castle Rock, Colorado, was the lead author. In the second and third papers, his co-author was Subhash Kelkar, Staff Technical Specialist for Durability CAE at Ford Motor Co.'s Product Development office.

** WOW is that vaguely defined aesthetic or functional feature that makes customers say, "I've got to have that." Because its definition is elusive, getting it into a design can be maddening.

Contact: **Dr Andreas Vlahinos**
Advanced Engineering Solutions
email: andreas@aes.nu

Dr. Vlahinos' clients include NASA, the U.S. Department of Energy (DoE), the U.S. National Renewable Energy Laboratory (NREL), IBM, Coors, Lockheed Martin, Alcoa, Allison Engine (part of Rolls Royce), Ball Corp., Solar Turbines (part of Caterpillar), American Standard, and PTC. A winner of a coveted R&D 100 award and holder of several patents, Dr. Vlahinos is also an adjunct professor of structural engineering at the University of Colorado-Boulder.