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The Probability of Optimum Design

Probabilistic methodology takes a different approach to predicting when things will break.

Louise Elliott

It’s hard to spell, worse to pronounce, and the vocabulary that describes it tends to be redundant. The word is "probabilistic." It basically means taking a statistical approach to random variations and determining probabilities. In engineering, it extends the variety of such design variables as geometries, temperature, and material properties to present a more accurate and detailed picture of how a design will perform and react to its environment. As cumbersome as the vocabulary may be, probabilistic studies (or synonymously, stochastic studies or Six Sigma Robust Designs) appear to be the next major step in optimizing designs with finite element analysis (FEA) tools.

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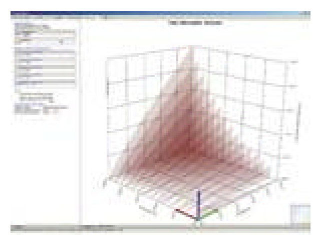
FEA itself is deterministic in nature—setting up models that have to face worst case scenarios because, we believe, if a design will survive the worst case we can imagine, it can survive anything. This leaves us all too often with over-engineered, unduly costly products. If, however, we can look at the full range of conditions the design will face, we can discover the most likely conditions that will cause it to fail. And then we can design for something closer to reality, rather than for the product’s apocalypse.



To understand the value of probabilistic methodology, says analyst Marc Halpern of Gartner Research (Stamford, CT; gartner.com), himself a registered engineer, it’s important to understand that "FEA solves differential equations describing a single circumstance. It can’t predict reality."

Halpern points out that FEA grew out of 19th century efforts to standardize engineering practices. At that time, he says, engineers used "hand-based methods for specifying requirements for quality, and factors of safety for unpredictable events. FEA evolved in the 1940s with aircraft design and the growing availability of computers to provide a level of predictability." But it’s still limited, Halpern says, to solving "equations with severe assumptions in them, modeling single instances."

Probabilistic methods aren’t new, but until recently, their use in engineering was limited to a few Ph.D.s, mostly working for aerospace companies, who wrote their own code for specific studies. Several high-level inventor-developers, including Stefan Reh of Ansys and his colleague Jacek Marczyk, who recently joined MSC.Software, also worked on creating user-friendly engineering applications for probabilistic methods. Veros Software introduced a number of probabilistic engines that can be used in conjunction with FEA programs a few years ago. And with the support of Engineous Software, which has its own iSight Six Sigma engine largely for automotive applications, Veros sponsors an annual Probabilistic Methods Conference. (Proceedings of PMC 2002 are available at probabilistics.com.)

Eric Fox, vice president of technology for Veros, started to develop probabilistic methodology when designing aircraft engines for Pratt & Whitney. He sums up the engineering value of these methods by saying, "Probabilistic studies look at many possible combinations of loads, and help to decide which are most typical. The results tell you the probability that you will exceed your load, and what situations will most influence something breaking. With that information, you can rank real scenarios and avoid over-design."

Probabilistic Method	Deterministic Method
• Input a range of values for each input variable • Obtain a range of values for each output variable	• Assume worst-case values for each input variable • Obtain a single output value for each output variable

Fox gives an example from his time at Pratt & Whitney: "The company wanted to reduce the weight of a rotor plate for an aircraft engine. Originally, the material property curve was based on a worst case scenario as affected by temperature. By taking a probabilistic approach that looked at rotor speed, pressure, blade loads, and snap fits, we were able to reduce each plate by four pounds —-and over the life of a fleet of engines, the savings in raw material and performance was $90 million."

Probabilistic studies can do more than save money, they can also help to engineer quality into designs, says Dr. Andreas Vlahinos, principal in the engineering consulting firm Advanced Engineering Solutions (Castle Rock, CO), and a user of Ansys probabilistic software. "Randomness and scatter are part of reality everywhere," he says. "Traditional deterministic approaches account for uncertainties through the use of empirical safety factors…(which are) based on past experience; they do not guarantee satisfactory performance and do not provide sufficient information to achieve optimal use of available resources." Previously viewed as intimidating, complex, and tedious, the probabilistic approach now integrated into such FEA codes as Ansys "makes probabilistic analysis setup simple if the control and noise parameters are identifiable."

Jacek Marczyk, managing director and chief scientist, Stochastic Simulation, for MSC, has written a number of books and articles (including "Putting the Uncertainty Back into CAE";

published by DE, it's available at DE Online, in the March 2002 issue). Marczyk says, "Any test or analysis of a complicated system is stochastic, or nonrepeatable. As a result, it is impossible to make any claims for the validity of a numerical model in a single test or simulation scenario." The answer, he believes, can be found in putting uncertainty—or scatter, or randomness—back into CAE, using such probabilistic methods as Monte Carlo simulation.

Monte Carlo simulation involves using a very large number of randomly generated scenarios (perhaps a wide range of results from physical tests done over a number of years) and then calculating the probability of various outcomes. Mathematically, the precision of a Monte Carlo simulation is proportional to the square root of the number of scenarios used—and with modern computers, these compute-intensive methods can be applied to increasingly complex problems. A number of other, faster, and less compute-intensive probabilistic methods exist as well, though their results are less reliable.

Finding the Data Can Be Difficult

Ansys has offered probabilistic solution methods as part of its software suite for about two years, under the name of Ansys PDS (Probabilistic Design System), to deal with FEA variations such as shell thickness, material properties, and attachment (number of nodes). Plans include geometric tolerances that will vary parts and perform parametric updates.

Stefan Reh, senior software developer and group leader of Probabilistic Design and Optimization at Ansys, says that acceptance of probabilistics takes time because engineers have a difficult finding all the necessary data. The company's DesignXplorer software adds a "quick start" approach and response surface method to the existing Monte Carlo method. Reh reports that Ansys is currently working with an aerospace customer on an implementation "that will involve retraining engineers to design products with a probabilistic approach."

Reh says, "We're developing platforms like DesignXplorer to make probabilistic analysis much more user-friendly, and easier to use. The system knows about the parameters the user has to describe for a study, and it automates that difficult part of the job by obtaining the needed data and linking it to applications."

Three Approaches to a Predictive Problem

METHODOLOGY APPROACH	DETERMINISTIC	STATISTICAL	PROBABILISTIC
Utilizes physics/behavioral/rule/process-based predictive model	✔	NO	✔
Considers inherent uncertainties, modeling uncertainties, lack of data, human error, measurement error	NO	NO	✔
Compensates for unknowns using	SF	SM	SM
Utilizes past performance data to improve accuracy	✔	✔	✔
Does not require event's past performance data to develop predictive model	✔	NO	✔

SF= safety factors SM = statistical methods

courtesy of Veros Software

Response surface method doesn't require as much data as the Monte Carlo method, and so provides faster—if less comprehensive—results. "If you have to research a lot of data, it's hard to get a quick start. Companies need to decide whether they need an absolute result—such as a definitive failure rate, which they can get with Monte Carlo simulation—or a relative result that will enable the creation of a better product design," Reh says. "With the relative approach, the software tells the user where he needs more data to obtain more accurate results, by indicating that the result is sensitive to specific factors, and also showing where to add data. It makes sense to get started quickly, and use the feedback provided by the system."

Probabilistic simulation requires a great deal of computer resources, and for speed, requires distribution across several CPUs. To lower the cost of using distributed probabilistic methods, Ansys now offers "batch child product" licenses. These allow several different computers to be used to process probabilistic analyses without requiring a full, interactive license on each. "Running a probabilistic study on one CPU can take a very long time. The batch child license just enables the software to run affordably."

MSC.Software won't announce a probabilistic product until closer to the end of the year, and the company describes its current products as deterministic, single point analyses. However, says Todd Evans, head of Media Relations for MSC, when the company does release a product, compute power won't be a problem. "Stochastic simulation requires three to four times more CPU power than deterministic, and MSC has its own Linux clusters, including machines using the Itanium 2 chip, for running the software. We will offer an entire system of software and hardware, with terabytes of analysis storage," Evans says. In addition, the company's work on design simulation data management systems should make it easier for users to access data necessary for probabilistic studies.

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