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Mechanical Design Synthesis

NEW PROCESSES FOR INNOVATIVE PRODUCT DEVELOPMENT

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A growing number of companies are using these approaches in helping to synthesize designs ... enabling the automaker to achieve a 50% improvement in product development efficiency, cost savings exceeding \$10 billion, and a compression of vehicle development time by 18 months.

“Although companies are often forced to spend millions of dollars to correct problems in the later stages of development, they generally underestimate the cost savings of early problem solving.”

Despite the best efforts at many manufacturing companies, some new products – and ones that are redesigned – flop in the market, often totally missing what customers want, need or are willing to pay for.

Some industry observers estimate that 35% to 50% of newly launched products miss their target markets. Such lack of success, even in a single product line, can have a huge negative impact on corporate profits, and in some cases, can threaten the survival of companies desperately trying to hang on in the face of fierce competition.

Some product failures can be attributed to radical shifts in the market or because companies are out of touch with customer requirements. But a large portion of the failure rate comes about because designers are not able to adequately address all the many engineering requirements needed to satisfy pressing market demands in today’s complex products.

Such a deficiency in product development typically isn’t due to lack of expertise, hard work, or experience, but rather simply not enough time to produce an optimal design that balances competing requirements. Automotive components must be lightweight for the highest possible fuel economy yet strong enough for maximum crashworthiness, for example. And the engine assembly must be as compact as possible while maintaining adequate airflow for proper cooling. Many of today’s products involve competing requirements. All are important, and neglecting just one can often result in a missed opportunity in the market.

Limitations of Conventional Tools

In the 1960s, an expanding range of computer-aided design (CAD) and computer-aided engineering (CAE) solutions emerged to help speed the task of developing such products. In particular, solid modeling and parametric design systems enable users to define and change 3-D geometry more quickly than ever. At the same time, simula-

tions based on finite element analysis (FEA) and other technologies have made tremendous strides in evaluating stress, deformation, heat flow and other factors. In many advanced applications, virtual prototyping approaches model and simulate complete products in their operating environments, predicting product performance in the early stages of development.

However fast these systems operate, the tools are intended to handle only a limited number of variables simultaneously. Users were thus faced with the tedious and time-consuming task of painstakingly running multiple simulations in attempting to iteratively zero in on an often elusive good solution that satisfies most of the requirements. More often than not, however, engineers develop the design based on only one of the most critical variables and neglect the rest, hoping any conflicts could be corrected later in the cycle.

The result is usually not an overall optimal design but rather – even in the best-case scenarios – one that just works and barely satisfies competing requirements. Often performance problems are encountered during prototype testing or production, necessitating repetitive redesign-build-test cycles until satisfactory performance is achieved, with several iterations usually required. This adds considerable time and cost to the development cycle, with automobile mock-ups costing \$300,000 to \$500,000 each and requiring months to build.

Also, designs are often far less than optimal, with quick-fix changes to meet scheduling demands solving isolated problems by usually detracting from the overall design. Components may be grossly overdesigned with needless weight and bulk to strengthen failed assemblies. When the product is finally launched, the window of opportunity may have closed, or performance may not satisfy customer demands and expectations. The target will be missed, and yet another statistic will be added to the manufacturing industry’s product

failure rate.

Next-Generation Approaches

A variety of technologies are coming together in providing a new class of tool that automatically optimizes designs based on multiple variables. Such solutions perform numerous iterative simulations based on boundary conditions and ranges of variables entered by the user. Design of experiments (DOE) technology generates simulations response curves based on various sampling and statistical methods.

A growing number of companies are using these approaches in helping to synthesize designs. In the General Motors vehicle development process, part of the synthesis process relies on up-front math models to provide insight into the tradeoffs between product requirements for given market segments, enabling the automaker to achieve a 50% improvement in product development efficiency, cost savings exceeding \$10 billion, and a compression of vehicle development time by 18 months. In this robust synthesis effort, the synthesis process relies heavily on multi-variable optimization methods that cascade down from full-vehicle simulations to variations in individual components.

Referred to as mechanical design synthesis, this class of next-generation solutions combines these optimization technologies with CAE simulation methods and parametric CAD into an integrated solution. Such tools define the optimal dimensions of a part so that stress or weight is minimized, for example, or that a resonant frequency is below a certain level. The result can be a numerical listing of values for a recommended design, plots showing the trends and influences of each set of variables, or an actual solid model of the optimal design as determined by the software. Also, users can make adjustments to any variable and see how these changes effect the optimized design.

In one of the first commercially available solutions

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of this type – DesignXplorer from ANSYS Inc. – a slider bar for each key variable is provided for users to dynamically interact with the model, changing parameters and seeing how this affects the overall design. Feedback is immediate, so engineers can run through multiple ‘what-if’ scenarios that would otherwise be too time consuming to perform with conventional tools.

Moreover, because the underlying mathematics of the solution does not limit the number of variables to be considered, factors such as manufacturability and other issues can be taken into account which would otherwise be considered after the design was completed.

In a goal-driven approach, users can study, quantify and graph various structural and thermal performance simulation responses as a function of design parameters for parts as well as assemblies. Bi-directional associativity with CAD packages allows designs generated through the system to be immediately translated into solid models. For the first time, performance simulation iterations can be done to match the rapid pace of parametric CAD iterations. Because of this speed and dynamic interactivity, mechanical design synthesis tools enable product teams to make informed decisions earlier in the design process.

This new class of software gives mechanical engineers the same benefits of higher-level design tools their counterparts in electronics have had for years in the form of electronic design automation (EDA) systems. Indeed, these solutions have become indispensable tools in the design of semiconductor integrated circuits (ICs) that involve so many inter-related variables. Mechanical engineers can now take that step to a level of abstraction, which allows them to optimize the overall design by effectively managing multiple competing variables.

Front-Loading Product Development

The mechanical design synthesis approach is most effectively leveraged in the early stages of product development when concepts are just starting to

take shape. The technology allows users to explore various product configurations, evaluate different part geometries and materials, and examine all the many tradeoffs inherent to product development. One of the greatest benefits of mechanical design synthesis and other simulation-based approaches early in development is that engineers have the time and freedom to efficiently evaluate alternatives, run ‘what if’ scenarios, and optimize the design. In this way, mechanical design synthesis serves as a valuable decision-support tool for engineers in determining the best direction for product development in the early stages of the cycle.

By studying product configurations in the early phases of development, engineers can make changes and refine designs easily and inexpensively. Studies have shown that the cost of change increases exponentially with each stage of development, thus making changes costly during detailed design, very expensive during prototype testing and tremendously high during production. Moreover, correcting errors after the product is sold can be prohibitive in terms of recall and warranty costs, sometimes causing economically catastrophic consequences for manufacturers.

“Although companies are often forced to spend millions of dollars to correct problems in the later stages of development, they generally underestimate the cost savings of early problem solving,” explains Stefan Thomke, associate professor of technology and operations management at Harvard Business School and author of the February 2001 “Harvard Business Review” article *Enlightened Experimentation: The New Imperative for Innovation*. “New technologies can provide some of their greatest leverage by identifying and solving problems upstream – best described as front-loaded development.”

Thomke cites one case where Toyota slashed development time and cost (including the number of full physical prototypes) by between 30% and 40% with a front-end loading initiative involving the use of early simulation in conjunction with

other process changes. In on-going efforts, the automaker is using CAE technology to identify functional problems earlier in the development process and also transferring problem and solution information from previous projects to the front end of new projects. In this way, the automaker expects to solve at least 80% of all design-related problems before the first prototypes are built.

Beyond operational efficiency, another advantage of front-loaded product development may be greater agility in responding to rapid shifts in market demand and buying trends. “In addition to saving time and money, exploiting early information helps product developers keep up with customer preferences that might evolve over the course of a project,” says Thomke.

According to Thomke, one of the most powerful simulation approaches in front-end loading is what he calls “enlightened experimentation:” the systematic testing of ideas for companies to create innovative products and effectively refine the designs. Enlightened experimentation uses technologies such as simulation to test ideas in computer software, increasing the number of breakthroughs by trying out a greater number of diverse ideas.

“Computer simulation doesn’t simply replace physical prototypes as a cost-saving measure; it introduces an entirely different way of experimenting that invites innovation,” explains Thomke. “The rapid feedback and the ability to see and manipulate high-quality computer images spur greater innovation: many design possibilities can be explored in real time yet virtually, in rapid iterations.”

Augmenting Engineering Creativity

Companies implementing mechanical design synthesis emphasize that that approach does not replace the creative aspects of engineering, but rather augments the ability of engineers to develop innovative designs, essentially serving as a way to most effectively take advantage of the talent,

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expertise and experience of a company’s technical staff.

“Mechanical design synthesis can be used in automating routine, repetitive tasks in evaluating the influence of many different variables, leaving the engineer more time and energy to devote to the original, creative and inspirational parts of the product development process,” explains Gordon Willis, president of Vulcanworks Inc., an engineering consulting firm that has developed a proprietary system based on these concepts.

Their Advanced Engineering Environment uses the ANSYS AI*Workbench application development platform in tailoring the solution to the processes, product types, and design goals of each client. Vulcanworks consultants first work with clients in determining the key variables for the product, then extract the design rules governing each of these variables. The resulting knowledge base is linked to simulation packages that evaluate the product structure over a range of parameters, with the system often performing tens of thousands of simulation iterations. The final optimized design is displayed in the form of a 3-D parametric solid model generated by another automated link. Plots and curves are also produced showing the sensitivity of the design to key variables.

This approach has been used on a variety of automotive mechanical systems such as suspensions, engine components, steering assemblies, and body structures as well as non-automotive projects including fuel cells and marine applications. Willis cites benchmarks where this design synthesis process has significantly compressed development times. In the re-design of an automotive frame structure to lengthen the wheelbase and raise occupant seating, for example, 720 person-days (12 people for 12 weeks) were required to complete the project compared to only 6 person-days (2 people for 3 days) using automated design synthesis. Similarly, work on a suspension system that normally takes 60 person-days was done in only 2 person-days.

“One of the crucial parts of the whole process – and what takes the most time – is establishing clear design goals right from the beginning,” explains Willis. “All the many design variables for individual components and assemblies cascade down from overall attributes that make the product unique, differentiate it from competitors, and motivate buyers to purchase it. Nailing down these key attributes that characterize this early in the cycle is essential in developing an optimal design, not only from a strict engineering perspective, but also from the standpoint of what will sell in the market to meet customer demand and expectations.”

Listening to the Customer

The use of buying trends and customer preferences as a way of setting overall design targets and product development goals is being used by a growing number of manufacturing companies throughout industries. Such goal-driven development is a foundation of mechanical design synthesis and is a move away from product-push development processes where efforts are directed at marketing products based mostly on how well they are engineered.

“Stories abound about well-designed, reliable and cost effective products that failed in the market because the public simply didn’t like them or failed to see a need for them. Such products may have been designed using the most advanced technology and meticulously tested to meet strict functional and safety requirements, yet development took place with little or no input from the customer,” explains Dr. Howard Crabb, president and CEO of consulting firm Interactive Computer Engineering. He authored the book *The Virtual Engineer* and spent more than 30 years at Ford Motor Company, where he led initiatives to implement solid modeling and predictive engineering performed at the concept level of design.

Crabb sees this as a major transition in manufacturing industries, with many companies today shifting to market-pull product development processes driven by customer expectations and

consumer demand. Automotive companies started making this switch in the 1980s, according to Crabb, and others have since followed suit. In the development of Boeing’s 777 commercial aircraft, for example, major input on new systems and support procedures was provided by customers in the form of airlines, pilots, flight attendants and service personnel.

“With consumer tastes more discerning and their demands changing more rapidly than ever, customers increasingly are now the focal point in product development. Market pull has replaced technology push and woe be to the manufacturer failing to respond,” says Crabb. “Studies have shown that recapturing customers once they are lost costs eight times as much as retaining them in the first place. Hence, the voice of the customer takes on strategic significance and is now a key element in the product development process. This major shift is truly a breakthrough.”

According to Crabb, ensuring the voice of the customer attributes are reflected in the product is a step-wise iterative process in which market requirements are first captured by research and benchmarking, which are used to direct assembly and subsystem concepts that are then translated into detailed component design and manufacturing requirements. The design is validated by the engineer throughout the process, particularly in the front end of development, through the use of CAE tools.

“Validation of the product design has been greatly enhanced through the use of computer-based technologies that allow initial analysis, test and simulation to be performed on the engineer’s desktop,” explains Crabb. “This iterative process results in the creation of a conceptual design that must be tested against target specifications to ensure that it meets or exceeds customer requirements for quality, value, comfort and timeliness.”

Emergence of the SuperDesigner

As companies use greater levels of up-front simu-

“...the SuperDesigner trend reflects a major effort to involve the entire product development community up front, early in the design effort. Rather than hurriedly trying to develop a design that merely works and occupies space, SuperDesigner and related initiatives strive to concentrate first on basic design requirements.”

lation in product development and mechanical design synthesis approaches based on multi-variable optimization, the roles and responsibilities of designers, engineers and CAE analysts overlap and converge toward what Don Brown, president of consulting firm D.H. Brown Associates Inc., calls a “SuperDesigner.”

“Broadly and fundamentally, the SuperDesigner trend reflects a major effort to involve the entire product development community up front, early in the design effort. Rather than hurriedly trying to develop a design that merely works and occupies space, SuperDesigner and related initiatives strive to concentrate first on basic design requirements. In other words, what customers expect in the end product. Then, a whole parameterized system can be assembled to address the full range of performance issues and tradeoffs.”

According to Brown, these design variables are the main drivers to assess whether the design meets these performance targets and typically involve a “control handle” in the design itself. Design variables may be exercised and evaluated through a variety of tools such as smart curves, automatic meshing, wizards and templates to drive the analysis.

“Such a system provides clues as to what questions need to be asked and actions taken to ensure that potential problems are addressed,” explains Brown. “This goal-oriented process of simulation and verification shows whether or not a design concept is worth further consideration. Today, a design may need to demonstrate that it is worth pursuing to be prototyped in hardware. Proof must be provided that it will work, and that it will meet market requirements. In most cases, this involves the evaluation of many what-if scenarios and multiple simulations in which designs are iteratively evaluated and refined. The more times a design

runs through such a virtual test environment, the closer the final product configuration is in meeting the design goals.

Implementation Strategies

Up-front simulation initiatives such as mechanical design synthesis are often blocked by the organization inertia of the traditional build-and-break cycle where prototypes are built, tested, fail and then redesigned again and again until the product performs satisfactorily.

“Changing behavior – changing the way business get done – directly confronts the daily habits of people accustomed to a build-and-break mentality,” explains Brown. “Overcoming this established way of operating is undoubtedly the greatest challenge in doing up-front simulation effectively. Workers in this entire process are very comfortable with the familiar build-and-break procedures. Moreover, up-front analysis may be regarded with skepticism by senior-level executives and managers, who absolutely need justification from a business standpoint for such a program.”

Brown notes that such initiatives often get stuck on a bottom-up “guerrilla phase” and instead need the backing of management from the outset. Generally, pilot projects are first implemented to demonstrate the new process’ advantages, with an assessment of engineering effectiveness generally getting top priority in jump starting a more extensive rollout of the methods across the enterprise.

As an example, tier one automotive supplier Eaton Corp. reduced time and cost 30% to 50% in the design phase of development through up-front simulation on specific programs, with the biggest improvement coming from the reduction in the number of design iterations. Their program focuses on designers performing first-pass analysis early in development, with the biggest improve-

ment coming from a reduction in the number of design iterations. In a traditional CAE environment, four or five days were required to evaluate and analyze a product such as a clutch, for example. That cycle fell to only a few hours with designers performing up-front CAE. Eaton also registered a 36% reduction as compared to sending a design to a CAE core group. By having designers and engineers do first-pass simulation early, overall design time falls significantly.

Such an improvement in engineering efficiency can easily translate into shorter cycle times and lower development costs as well as improved quality. This type of determination is probably the easiest to justify the time and expense of implementing up-front simulation-based processes such as mechanical design synthesis.

More difficult to quantify are higher-level benefits of these initiatives. Reduced time to market may mean greater market share for a product. Also, developing products that better reflect customer preferences and buying trends in the design can increase sales and revenue. Moreover, the greater capabilities engineers have through simulation-based approaches in developing more innovative designs has the potential for companies to strengthen their position in existing markets or possibly penetrate entirely new markets.

Achieving these broad business objectives requires executive planning and vision, of course, along with a commitment to integrate new processes such as mechanical design synthesis and simulation-based design into a company’s long-term business strategy. Using such an integrated approach, companies can leverage these powerful technologies to their best advantage by implementing the solutions and achieving beneficial results while less astute competitors are just waking up to this new way of working.