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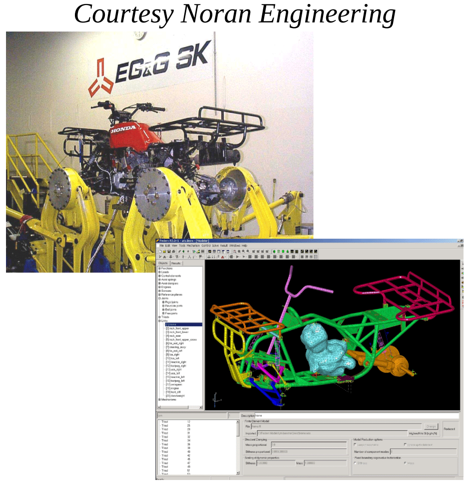
# Virtually perfected

**By: Elisabeth Eitel**
**Motion System Design**

**Simulating moving designs is easier and more useful than ever.**

*Courtesy Noran Engineering*




**Kinematics software like NEiMotion can virtually determine forces, stress, deformation, fatigue, and life. Applications include suspension systems, construction equipment, robotics, production fixtures, hand tools, and office chairs.**

Picture a classic four-bar mechanism. With a basic spreadsheet, some knowledge of complex numbers, and input information, you might plot output acceleration and speed in a couple hours. But what if geometry changes, or the full three-dimensional situation needs analysis? Here, kinematics software makes building models infinitely easier. Increased connectivity is even allowing the placement of specific component profiles into models, and VRML and OpenHSF web viewing. And if our supposed one-degree-of-freedom system might actually be deforming under load, finite element analysis (FEA) can make our model highly realistic.

That's why everyone from Fortune 500 companies to individual consulting engineers is using analysis software. "It's very popular with consultants and designers, because it allows them to do the same things that larger competitors do — allowing them to design in areas where they might not have been able before," says Bob Williams, product manager, ALGOR Inc., Pittsburgh.

**Kinematics put to sophisticated use**

Returning to our four-bar example: Once mates are defined in a CAD assembly, kinematics software, which holds all links rigid, can animate the model. In the past, this was basic stuff. But now, more software is allowing designers to enter parameters like motor speed and motion for full inertial conditions. Output is generated as equations describing power requirements and joint reactions. The trajectories of motion can verify the movements of industrial robots, test tool paths, establish power requirements, and more. Simulation results can also be used to design systems in reverse, by converting trajectories to create new part geometries — for cam profiles, for example.

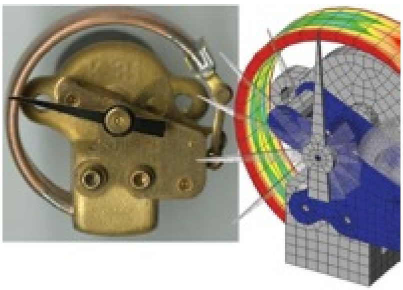
Cross-connectivity goes one step further in the development of mechatronic parts. In typical machine design, builders get requirements for a new project, design a controls scheme, and mechanical and structural engineers build the physical machine — and *then* the controls engineer implements his logic onto the machine to see if it works. "But with mechatronics toolkits, you can test controls algorithms even before any physical model is built," says Hari Padmanabhan, of SolidWorks Corp., Concord, Mass. To illustrate: Design & Assembly Concepts, Inc., Leander, Texas, recently used mechatronics software tools for motion optimization and collision detection on a solder tin dip machine to fully integrate their controls, programmed through LabVIEW (of National Instruments Corp., Austin) with SolidWorks and COSMOSMotion within the program.

"So say you have a six-axis robot, where each axis is controlled with a motor," says Padmanabhan. "Application Programming Interface (API) WinHelp allows, through Visual Basic, communication of control information with COSMOSMotion, including power requirements and so on." The actual physics of the situation profiled in the mechanical CAD assembly is put under the electronic control, for full virtualprototyping.

Other product suites also work as cohesive units to facilitate development for the creation of products like airplane-wing flap actuators and packaging machinery. "Our TK Solver, for example, rapidly builds mathematical models of mechanical pulleys, screws, clutches, and electrical and hydraulic models," says Jack Marathe, president of Universal Technical Systems Inc., Rockford, Ill. Their Galaxy software takes it one step further, bringing together information from the Solver, Microsoft Excel, Visual Basic, and FEA analysis so that whole systems can be simulated; different levels of information, or portions of a design, can then be shared with people on a project, or workers under contract from another company. So, suppose you have a motor-powered system driving a gearbox, belt drive, or screw, down the line. The motor generates power and motion, and may hold its speed, or drop off, to move a robot arm or table. "Well, all the analysis for that can be put into a building block. Then designers can very rapidly see downstream how the system will move — and share their models and information," says Marathe.

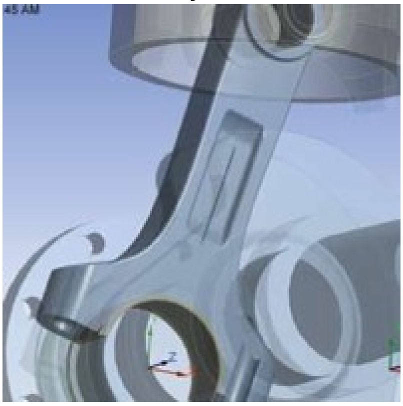
**FEA breakdown**

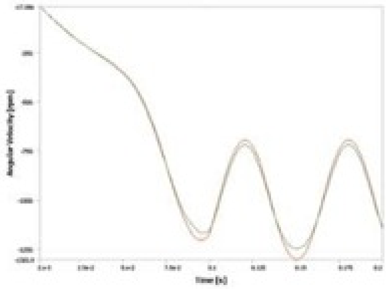
Until fairly recently, finite element analysis — linear, that is — has been one of the most common computer-aided engineering tools for putting convenient CAD files to higher use. But sleeker software and faster processors are increasing the use of nonlinear analysis. Mathematically speaking, how do the two differ? "The term *linear* implies that system properties do not depend on a system state," explains Vladimir Podnos of Tera Analysis Ltd., for QuickField, Toronto. Graphically these



**A Bourdon tube pressure gauge modeled and analyzed with ALGOR's Mechanical Event Simulation software shows the motion of the indicator needle as pressure increases within the tube — and resulting von Mises stresses.**

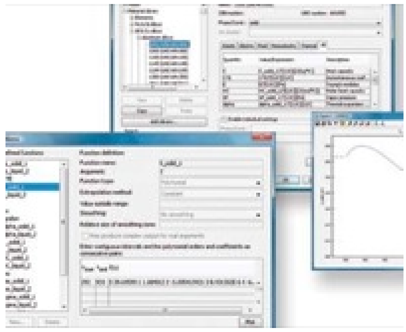
*Courtesy ANSYS*





**Superelements reduce degrees of freedom and make full-system FEA modeling faster. Here, a rigid model's reaction to load is plotted in red; the reaction of the flexible superelement model is shown in green.**

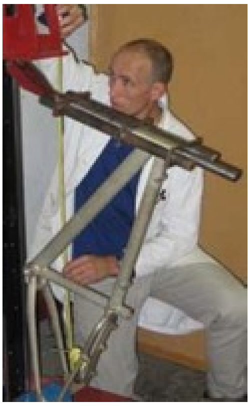
situations plot as a straight line: On temperature versus thermal flux, or displacement versus stress, or magnetic field intensity versus flux density, for example. Nonlinear problems, on the other hand, include parameters that change with a system state. So, if system parameters are fixed and independent, equations need solving only once. "But for nonlinear systems, there must be some kind of iterative process in the software that goes on until convergence, when the distribution stops changing," says Podnos.



*Courtesy COMSOL Inc.*

**Materials libraries can contain the property functions for thousands of materials. They allow users to find suitable materials with flexible search — by name, UNS (Unified Numbering System) number, or DIN (German Institute for Standardization) number.**

**Stresses from impact**



**A mountain bicycle frame manufactured by K2 Sports Corp., Seattle, was tested using ALGOR's MES software to determine the stresses caused by the impact of a 22.5-kg object. The results agreed with a physical impact test.**

Most processes are nonlinear, so linear analysis is suitable for fast, rough approximation of values, or when system parameters are supposed to be stable within a (typically narrow) operation range. But the stress-strain behavior of elastomer gears, rubber belts, and other flexible transmission components can *only* be accurately modeled with nonlinear FEA — for example, as under von Mises stresses.

But there is another application for linear analysis. For stress problems, some software, particularly simplified software more geared towards electromagnetics, only returns linear results. These model all mechanics as coupled to electromagnetics — say, as stresses in transformer windings due to electromagnetic forces, or stresses within electric cable parts due to heat caused by current flow. "It's just enough simple stress analysis for electrical and magnetic engineers to briefly check the mechanical stability of their designs, but avoid overly complex stress models," Podnos explains. "Our QuickField software solves nonlinear problems for heat transfer and dc and transient magnetics. But linear solutions are generated for electrostatics and dc conduction, ac magnetics, and stress."

**One further distinction**

Linear versus nonlinear isn't the only level of distinction in software analyses. "Much analysis software performs either linear or nonlinear *static* stress analysis, depending on what type of materials are involved," explains Williams. With this approach, there are many hand calculations and assumptions about what loads occur based on how components are moving and interacting because static analysis only applies to static loads. Often, this software converts an assembly into a kinematics system, which determines motion and forces at linkages, applies those back to an FEA model, and then grinds through a series of linear static stress analyses to calculate stresses.

"If you're dealing with a solid metal-type assembly, and you're just trying to capture that motion, which is common — the large part of the assembly really isn't all that interesting or critical from a stress standpoint. Rigid-body kinematics software may be sufficient for someone who strictly needs to model such motion," says Williams. But suppose your design's connections include bearings, gaskets, and rubber fittings. "Here, assuming that these connections are rigid and there is no movement or deformation is invalid," adds Williams. As in the human body, fittings and the way things connect critically affect the way an assembly behaves. "Our Mechanical Event Simulation, on the other hand, calculates real motion and resulting inertia, and makes *that* the driving load in analysis," says Williams.

So, consider a part that is moving 10 mph. Instead of performing several calculations to determine what kind of load that might cause in a component, a designer can simply type the value for speed in a field — and the software calculates the different inertial loads at various points on the body. Stresses resulting from that motion are also calculated. "Flexible-body models allow more realistic simulation of connections; the fully nonlinear dynamic process determines not only motion, but associated stresses as well — similar to nonlinear transient stress analysis, but modified to run more efficiently," says Williams.

Some software simplifies sections of a component into superelements — most often, by regular substructuring or by component mode synthesis, in which DOFs at interface nodes are retained, and all others are eliminated by matrix condensation. "Superelements retain model flexibility but reduce the degrees of freedom, for efficient solutions," explains Sheldon Imaoka, ANSYS Inc., Canonsburg, Pa.

But Imaoka suggests another way. "Our superelement Component Mode Synthesis (CMS) appends a regular substructure with generalized coordinates to improve the accuracy of super-element response to dynamics," he explains. The superelements are suitable for nonlinear transient problems because they can be used in largedeflection nonlinear analyses — because of the reduced DOFs (that is, interface nodes and generalized coordinates) and accurate dynamic representation. "CMS superelements can also be used in static, modal, harmonic, and response spectrum analyses," notes Imaoka.

**Better reference materials**

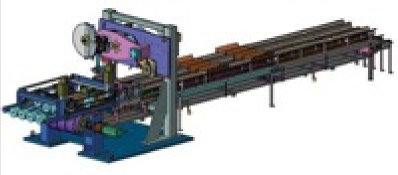
Similar to the way iTunes allows feeds from the Gracenote database, design software is allowing more access to reference libraries. For example, Roark's book on stress and strain is a classic in engineering, published since 1938. It has about 5,000 formulas organized by part geometry. "Well, we've computerized the whole book with software that allows the reference to be used more easily," says Marathe. Designers can search quickly to gather information on structures in their own projects, through quick finder fields. The tool is useful during design, and to cross-check FEA software results as well, serving as a reality check for answers.

In addition, cross-brand partnerships are now allowing users access to vast online materials data. "We have relationships with MatWeb and other related companies so that engineers can pull information about materials directly off their site and into the analysis software," says Williams. So, designers have access to tens of thousands of materials profiled — and not just the thousand or so that might come in a typical FEA program library.

Too, some software allows statistical prediction of component performance. "Size and materials is never perfectly consistent. Our Monte Carlo allows definition of the likely variability in values, and then, using statistical methods, it outputs ranges of say, stresses, that final components will experience," says Marathe. Uncertainty is removed, and users don't need to be experts in statistics to perform the analysis.

**Easier communiCADing**

Imagine a machine that produces 1.4 million rolls of toilet paper or 2.4 million feet of paper towels per day. Paper Converting Machine Co., Green Bay, Wis., designs such machinery for companies like Kimberly-Clark and Procter & Gamble. Before, when Paper Converting Machine Co. was designing and building these machines, they managed separate bills of materials in their CAD and enterprise resource planning systems. This introduced errors and delays in development and delivery.



**This rendering is of a Prolog LT log saw used to slice product at 250 cuts per minute for tissue and 125 for towel.**

Now the company uses design analysis (SolidWorks 3D CAD, and COSMOSWorks, Motion) from SolidWorks, as well as their product data management (PDM) software to manage CAD data while collaborating with engineering teams in Europe, Brazil, and Japan. The software lets multiple engineers work on the same design without errors, to accelerate development while minimizing rework. Its stability and integration with the CAD software also prevents data loss.

"The amount of data you're generating with parametrics, including the relationships between assemblies and parts, is exponentially higher than with 2D," says Thad Perkins, director of mechanical engineering at Paper Converting Machine Co. "Our PDM tool securely manages several hundred thousand 2D and 3D designs."

**Speedy iterations for speedier cars**

Based in Alfta, Sweden, Leanders Brothers Racing is a team that won the 2006 FIA European Drag Racing Championship, and is the current grand champion. Leanders uses a custom clutch unit that provides enhanced heat dissipation to make the clutch more durable. The 10-in. unit has three discs and no bolted facings, which is what improves heat dissipation during races and makes maintenance easier. "Our clutch is a result of experimentation with different designs," says Jorgen Leanders, the team's chief engineer. "Software helped me capture the best design through trial and error." Leanders uses software from IronCAD LLC, Atlanta. Changes are possible even far into the design process. In fact, Leanders is currently developing an 11-in. clutch (with and without a ring gear) that will be used to transfer torque from the starter motor pinion to the flywheel. Adds Cary O'Connor of IronCAD, "Parametric capabilities allow constraint-driven variations of the clutch design, or changes can be made that do not abide by constraints."

**Under the hood: Math**

There are a myriad of algorithms utilized in simulation software. For solving one-parameter nonlinear systems, for example, some software might use the iterative Brent method; it usually works better than simple linear interpolation, because usually, nonlinear functions are not particularly smooth.

For multidimensional optimization, where results depend on several parameters, the *Nelder-Mead* method is a classic. Here, the minimum is approached by steps, one coordinate at a time. A function's behavior is extrapolated to generate new test positions. Each reiteration, the algorithm replaces one test point with a new one — replacing the worst with one reflected through remaining points — until the software reaches a tipping point, and shrinks the simplex towards the best.

But turning it up a notch is modeling vibration — one of the most computationally demanding tasks in analysis. Algorithms abound: Rayleigh quotient iteration, Jacobi-Davidson, Davidson, LOBPCG, and subspace iteration. One new software based on eigensolvers combines the memory savings of iterative solvers with the robustness of Lanczos. "Our PCG Lanczos eigensolver determines natural frequencies and mode shapes using less computational power, often in less time," adds Jeff Beisheim, senior development engineer, ANSYS Inc., Canonsburg, Pa.

One command is its *level of difficulty*, which fixes convergence problems that typically occur when elements are oddly shaped. Higher levels replace the PCG with a Sparselike direct solver, so the program behaves more like a Block Lanczos.

**FEA for the masses**

Even 50 years ago, finite element analysis existed, but was used only by those bold enough to develop an FEA system themselves. There was no need for an easy user interface or quality results presentation, because the pioneers of FEA were highly trained specialists, often working at universities, with detailed understanding of mathematics and programming. Platforms were mainframes or UNIX workstations.

Fast forward: When computers spread in industry, PCs became powerful enough to handle the huge processing job of meshes and matrixes for systems of equations so essential to realistic models. "FEA programs are now more polished, but can still require deeper understanding," says Podnos.

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