Getting the Right Answers

By Dominic Gallello & Doug Neill – MSC Software

Getting answers that accurately correlate to physical test is the "raison d'être" for mathematicians and engineers who create CAE applications. Many people have asked me over the years why MSC's products provide an extremely high level of accuracy. The answer can be found in the history that created a culture.

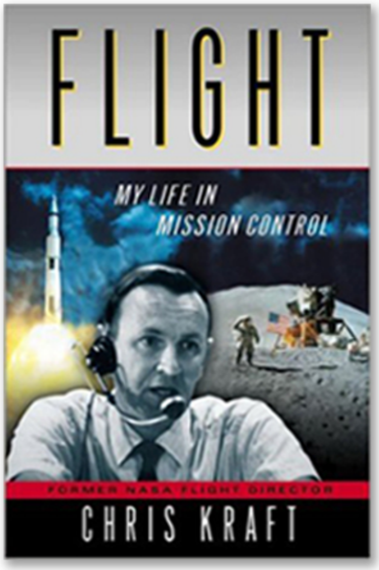
The foundation stones of MSC were laid in the 1960's during the race for space. Because of the obvious defense implications, this was a national imperative. It was time of virtually unlimited government funding for advancing engineering methods – long nights and weekends; country first and family second.

No matter how much on-the-ground physical testing you did, nothing could completely mimic the ultimate physical test of actually launching the rocket. Nothing can add more to the sense of urgency and responsibility than the fact that humans would be sitting on top of the rocket. Getting it right the first time was essential!

With this backdrop, the engineers at MSC had to deliver the right answers. There has always been an enormous sense of pride in our mathematicians that their chosen profession could advance humanity. Their efforts were quantified in terms of contributions to society in 2003 by NASA: (http://www.nasa.gov/pdf/251093main_The_NASA_Heritage_Of_Creativity.pdf)

2003 Annual Report of the NASA Inventions & Contributions Board

GSC-00, 092-1	NASTRAN Efficiency Improvements & Enhancements	$10 billion+



Chris Kraft started his career as an aeronautical engineer with the Space Task Group, the predecessor to NASA. He was part of a small team responsible for putting America's first man in space. The head of the division gave Chris a simple directive,

"Chris, you come up with a basic mission plan. You know, the bottom-line stuff on how we fly a man from a launch pad into space and back again. It would be good if you kept him alive."

During the sixties, Kraft was a household name in America. He appeared on the cover of the August 27, 1965 issue of Time Magazine. He served as NASA's Flight Director of Mission Control from Mercury through Apollo.

Best regards to
Dominic Gallello
Chris Kraft
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Nastran was a very important factor in structural analysis for space vehicles. [illegible] programs were a necessary factor in those space successes.

Chris Kraft's note to me on how Nastran was a critical factor in space flight success >>

Delivering the “right” answers means far more than accurately solving a set of equations. It means building the right physics into those equations. Not necessarily the most precise or the most detailed physics, but instead the most useful. And, these answers needed to be obtained within the time frame of engineering decision making. That means the tools needed to be robust, predictable and fast. The review of delivering the right answers can be broken into four areas: the elements (in finite element analysis), materials (allowables and failure), performance and the high level “solutions” to the engineering problems.

Elements

First, and perhaps foremost among the key technologies to produce the right answers was the use of the finite element method for structural analysis. FE technology was young at the time MSC started with MSC Nastran, and the “basic” element library of membrane shells, rods and bars was adequate for only the basic responses of structures.

At MSC, a set of engineers and mathematicians set out to build the best set of elements for engineering. Conceptually, finite elements are simple things and getting the right answer appears to be simple, too. But that is not the case. Early work by MacNeal and Harder led to the development of the industry standard membrane bending shell element (the CQUAD4). It remains the best element of its type. It is used reliably and with confidence every day by hundreds of engineers even though, theoretically, it shouldn’t be possible to get a valid answer on a low order quadrilateral shell. By working with customers and using imaginative approximations, MSC developed approaches to give the right answer even when theoretically, the answers should be incorrect. An example is the work done to identify the source of error on a curved shell induced by the drill DOF singularity on the standard “5-DOF” shell.

Over the 40 years of Nastran development and use, we have retired many “good” elements in favor of better ones (e.g., the IHEX family, the quadrilateral membrane elements and several versions of the shear panel have been replaced with better ones). In addition, MSC continues to develop new “higher abstraction” elements, like the seam and spot WELD elements, the BOLT elements and extensions to the “infinite flexibility” (load spreading) element, the RBE3. Recently, MSC worked with a major airframer to develop a form of the RBE3 that is stiffness weighted rather than topologically weighted. This allow improved accuracy in large rotation geometric nonlinear aero-servo-elastic simulation of highly flexible aircraft. These elements allow users to model specific complex phenomena within the context of a load path derived by accurate full FE models. In the case of the WELD element, we have worked directly with customers to correlate our behaviors to test results and to the engineering metrics (sizing, spacing, and manufacturing processes) that the engineering analysts will use to make their design decisions.

Materials/Allowables and Failure

In the early days of finite element simulation, MSC implemented the basic materials models to allow engineers to simulate the right dynamical behavior (stiffness and mass). However, it quickly evolved to looking at stress/strain and validating that the simulated behaviors did not exceed the materials’ failure points. From these basic materials, MSC implemented failure theories (Von Mises, Tsai-Wu, Tsia-Hill and many, many others). These computed values allowed analysts to quickly check for exceedance of design criteria and to take action to change the design. Changing simulation from a validation tool to a design tool was one of the key evolutions in the CAE industry and the build out of materials and failure prediction was a key aspect of that evolution. Attaching design criteria and failure prediction to the models was one of the big steps forward.

Today, the development of design allowables (limits on the material behavior before failure mode is excited) is an ongoing process. Material models are constantly under development by our customers and by researchers. These models attempt to capture everything from microscale phenomena to multi-physics and are always a combination of behavior and failure prediction. Even “progressive failure” is used today wherein the predicted local failure causes an approximate degradation in material properties so the load path redistribution can be simulated. Thus engineers are not limited to avoiding every failure, but can design their systems to accommodate some failure while avoiding catastrophic failure.

Performance

Getting the “right” answer does not mean the most accurate physics or the most complete solution: it means getting an accurate outcome within the time available for the engineering method. If you get the perfect answer after two weeks of computation, it is often too late to influence the design—the iterations in the concept have moved beyond your model and the answer is no longer relevant. To that end, two important factors have been key to MSC’s drive for “getting it right”. First is the raw performance of the application (robustness and computational performance) and the second is evolving the basic solution to accommodate changes in the industrial application of finite elements to the engineering problems.

The most basic view of the increasing demand for scalable performance is the expansion of the physics and criteria that are computed using the finite element method. More detailed data recovered from a refined mesh topology now yield not only basic structural dynamics, but also failure criterion (or even use these criterion to drive directed search methods like gradient-based optimization in our Solution 200). The models become bigger because the detail of the physics captured in the model and the volume of the data recovered grow. The WELD and QUAD4 experiences noted above are also examples of “evolving the engineering method” because the surface normal correction only became important when the elements became smaller and customers started seeing and measuring the drill singularity and resulting stress from misaligned degrees of freedom. And the rotational stiffness of the weld element has been shown to be sensitive to mesh density so that, as the automotive community has moved to sharing mesh topologies between crash and NVH models, the weld element accuracy degraded because the inherent “width” of the weld itself was partially described by the element dimensions in the vicinity of the weld.

The most significant impact of this evolution in the model size is in the demand for new numerical methods to solve more linear algebra equations more quickly. The time needed to make engineering decisions is a direct driver on time-to-market and competitive advantage. As the role of simulation in the engineering process grows, so does the need to solve the resulting equations in time to influence that engineering decision making process. It does not seem that long ago that the number of equations to be solved was in the range of 1,000 to 65,000. Today, as crash simulation models drive the “common” mesh model, typical models are 20,000,000 equations and “big” ones are 5x that number. And we continue to evolve our technology to accommodate these production simulation models

From the outset, MSC has been focused on high performance and scalable linear algebra methods. Firstly, every method for linear algebra implemented in Nastran allows for the spooling of data between memory and disk. Of course, the older methods (from 1970) have very different assumptions about how much disk and how much memory are typically available! Commercial versions of a Block Lanczos eigensolver appeared long ago and resulted in a major step forward in computing modes—which form the basis vector set for reduced dynamic equations. Complex eigensolvers, basic linear equation solvers, iterative equation solvers, exploitation of GPGPUs (MSC Nastran was the first commercial FE code with support for GPGPUs) and others all have been implemented into MSC simulation tools to address both general and very specific solution needs.

Parallel computing is another tool to get the right answer in a timely way. First is multi-threading (or what MSC named “shared memory parallel (SMP)” when we implemented the first versions nearly 20 years ago. The other parallel methodology is called “distributed memory parallel” and the name that MSC used has become the general term. MSC Nastran is one of the few codes in the world that has implemented methods that support combined SMP and DMP parallelism. We continue to aggressively pursue these methods to increase the size of the problems that can be solved within the time restrictions of the engineering cycle.

Solutions

In addition to the core FE technology, and robust scalable linear algebra methods, another important part of getting it right is the good engineering approximations that are implemented at the solution level. Keeping your goal focused on giving the engineer what he/she needs to make a decision while NOT producing a large volume of spurious data is often the key. For example, MSC engineers developed an acoustic sensor to return the sound pressure level (SPL) only at locations of interest rather than returning generic “FE resultants” on the fluid volume. This allowed rapid computation of the data quantity of interest.

We also developed and/or implemented low level methods like bubble functions, reduced integration and other (trade secret) approximations in the element formulations to avoid locking and produce the right answers on element responses even when theoretically we should not.

Damping was important early in our history. Complex eigensolutions, frequency response and transient response were the foundations of systems simulation at MSC. If you study damping in our solutions, you can see almost every methodology for approximating damping that has ever been studied. There are no physics to predict damping, so instead, structural damping, viscous damping, modal damping, material damping and others were implemented to allow our customers to experiment and determine the best approach for their class of structures. Recently, we co-developed a method that takes the common modal damping and spreads it over the physical degrees of freedom so that it can be applied to non-modal (e.g., nonlinear) structural dynamics problems.

Getting it right is also about providing information to change a concept to make it better (lighter, stronger, more easily manufactured, etc.). MSC Nastran was the first commercial Finite Element code to implement optimization INSIDE the solver. Implementing research on semi-analytic gradients and key work on gradient based approximations, we delivered a computationally viable method for solving large scale optimization problems. Recently, we have added heuristical methods to seek a global optimum and also to allow multiple models to participate in a single optimization problem.

Summary

Our foundations were laid in the race for space and we have never forgotten that getting answers that accurately correlate to physical test is our prerequisite. But we also have worked to expand the applicability of first the finite element method and now general CAE to help drive engineering design. We thrive on the endless quest to get the right answer. First we will get it right. Then we will make it fast. Then we refine it all to make it robust and timely for the engineering decision makers to use FE comfortably to make their decisions quickly and with confidence.