Virtual Prototyping Vs. Physical Prototyping

Designers have two available options when making analysis decisions: numerical analysis (virtual prototyping) or analytical analysis verified by prototyping and empirical measurement (physical prototyping).

Bill Jennings and Kevin Bourne

Today's product development environment is a jungle. In this hostile wilderness roam a host of vicious predators — compressed schedules, inadequate resources, product liability, stateside and offshore competition, cancelled projects, shifting priorities, budget cuts, etc. The engineer must artfully weave between these obstacles to reach his ultimate goal — product release. The success of every product development effort is measured by three criteria:

- Adherence to the schedule.
- Adherence to the budget.
- Adherence to the design requirements.

The endeavor that meets these three items is truly successful. Unfortunately, it also is few and far between.

Design Requirements

The American public is notoriously unforgiving of their consumer products, especially when compared to the rest of the world. In Europe, if you drop your cellular phone onto the pavement, simultaneously kicking it under the wheels of an oncoming taxi, you scold yourself for being clumsy and buy a replacement. In the U.S., you return the pieces to the dealer and demand a new phone. Consequently, U.S. consumer products must be reliable, robust and rugged. They also must be of the highest quality while being priced extremely competitively. Largely the designer shoulders the burden of meeting these mostly diverging requirements. He/she must meet increasingly difficult design requirements, within budget and in ever-decreasing product development schedules.

Many tools have evolved over the past few decades to aid the designer in his/her tasks. Computer aided design (CAD) and computer aided manufacturing (CAM) greatly expedite the design and tooling, respectively, of new products. Various types of rapid prototyping, including fused deposition modeling (FDM), stereolithography (SLA), and selective laser sintering (SLS) provide early proof of concept models. Various translation software packages, such as IGES and STEP, allow sharing of CAD/CAM 3-D data between design groups and disciplines. Laser scanning and coordinate measuring machines (CMM) greatly facilitate reverse engineering. Fast turn soft tooling generated by methods such as RTV molds, high-speed milling, centrifugal casting, etc. can provide near production quality parts. Numerical analysis tools such as Algor, Ansys and MSC Nastran provide linear and non-linear solutions for complex systems exposed to static, dynamic and thermal loading, shock, vibration, etc.

While there are many tools at the designer's disposal, not all of them are optimum or even desirable for any one instance. The primary goal of the designer is to meet the system requirements. However, in order for his/her project to be deemed a total success it also must meet the budget and schedule goals. It is the combination of all three of these goals that will determine which tools he/she must use.

The decision to employ virtual prototyping (numerical analysis) or physical prototyping (analytical analysis with prototyping and verification) must be evaluated on a case-by-case basis.

Analysis Techniques

Perhaps the most crucial facet of product development is the analysis of the system. This ongoing investigation can greatly define the industrial and detail mechanical design, material selection, production processes, etc. of the product. The designer will typically come to a crossroad early in the design process where he will need to make analysis decisions that will be critical to the success of the product development. The two options are:

1. Numerical analysis or "virtual prototyping."
2. Analytical analysis verified by prototyping and empirical measurement or "physical prototyping."

The decision of which route to follow is primarily influenced by schedule, cost and design.

Numerical

Numerical analysis methods include finite element analysis (FEA), finite difference and finite boundary. These tools are recommended for more complex problems, e.g., irregular geometry, temperature or position dependant material properties, nonlinear boundary conditions, etc. Their origins can be traced to the early 1950s when solutions were first generated by hand. This was a tedious and time-consuming process in which the first step was to separate spatial and time coordinates to form a mesh of nodes. Next, approximations were made to the derivatives of the governing equation to convert the differential equation to an algebraic difference equation.

For example, in a thermal management problem, Fourier's equation for heat conduction would be employed. A set of linear algebraic equations was derived containing as many unknowns as mesh nodes. The finer the mesh, the more accurate the solution would be. The linear algebraic equations were then solved by matrix inversion or by iteration. In the 1960s and early '70s, engineers derived custom algorithms to solve numerical problems on mainframe computers and programmable calculators. By the 1980s the widespread use of personal computers spurred the emergence of high-end programs that gave the engineer the ability to create analysis models in a similar fashion as CAD, i.e., with curves, Boolean operations, etc.

Today's numerical analysis programs provide preprocessing and postprocessing capabilities through a modern graphics user interface (GUI). During the preprocessing phase, 2-D and 3-D models are created and boundary conditions applied. Solutions can be found using a variety of methods and the results can be viewed in the postprocessing phase. Animation of part movement, values of stress, deflection, vectors, thermal gradients and plastic deformation can be shown in graphs, tables and as color fringe patterns superimposed on the analyzed part. The data can then be exported in various formats such as BMP, TIFF, JPEG, VRML and WMF for use in text documents.

Analytical

An alternative to the theory intensive numerical strategy is to use an analytical analysis approach with subsequent prototype generation and verification testing. This method places more emphasis on empirical data taken from production representative hardware rather than analysis.

First, hand calculations are performed using the applicable basic laws of mechanics, thermodynamics (heat transfer), fluid mechanics, etc. Once a solution is obtained, a reasonable safety margin is typically applied. The design can be developed/refined accordingly and prototypes generated. While subsequent testing of the prototypes may reveal specific areas of additional enhancement, the original design will likely be verified. Production tooling can now safely follow.

The advantages and disadvantages must be carefully considered in order to choose the correct path at the design analysis juncture.

Pros and Cons

There are definite advantages and disadvantages to both numerical and analytical analysis:

Numerical Analysis

Advantages

- Able to support analyses of complex geometries and assemblies. It must be noted that as the intricacy of these systems increases, the effort, skill, computing time, hardware capacity and analysis software tools can increase exponentially.
- Able to solve for non-linear, non-steady state and dynamic scenarios.
- Provides specific and detailed values of results as they vary across the system.
- Provides several formats of graphical data interpretation.
- Facilitates finer, more precise design optimization.

Disadvantages

- High software and associated hardware cost.
- Long learning curve/complexity requires dedicated technical personnel.
- Typically must be outsourced, resulting in risk path for development schedule.
- Expensive.
- Long leadtime.
- Data is theoretical, must still either prototype or hard tool and test for final verification.
- Oftentimes must make simplifications to geometries, systems, etc. to facilitate analysis.

Analytical Analysis With Prototype Generation/Verification

Advantages

- Fast.
- Provides empirical data/verification of design from actual hardware.
- Analytical analysis and testing can typically be done in-house.
- Relatively inexpensive.
- Prototypes are typically extremely representative of final product.

Disadvantages

- Prototyping usually must be outsourced, resulting in risk path for development schedule.
- Typically must include sizeable safety factors to ensure conformance to the design requirements.
- Usually must make simplifications to geometries, systems, etc. to facilitate analytical portion of analysis.

Examples

These advantages and disadvantages must be carefully considered in order to choose the correct path at the design analysis juncture. Every product development effort will have its own unique circumstances and requirements that will influence this decision, as is illustrated in the following examples.

Consumer Electronics

The average police mobile radio must dissipate about 40 watts of power. This is accomplished by conduction, convection and radiation through a die cast aluminum chassis. Typically, marketing will provide the designer with a desired maximum weight and volume. Engineering will specify a duty cycle and maximum ambient, component and operating temperatures. The development schedule for radio and telecommunications products is generally aggressive and competition is fierce. A review of the system requirements and accompanying development goals clearly indicates this to be an ideal candidate for analytical analysis followed by prototyping and testing, or physical prototyping.

A hand calculation that uses either the first law of thermodynamics (energy balance) or a thermal circuit method can be applied that takes into consideration the given boundary conditions. For the energy balance method, the heat generated must equal the heat dissipated through the three modes of heat transport phenomena, i.e., conduction, convection and radiation. For the thermal circuit method, various resistors are used to simulate the effects of the transport phenomena. This method is similar to solving a direct current (DC) network. The change in temperature is analogous to voltage, heat with current and the thermal resistance to electrical resistance. Typically, these methods are used for one-dimensional, steady state problems.

Note: If a more complex solution was required, a multidimensional analysis is recommended. A multidimensional method will most likely involve using higher order mathematics such as differential equations (Laplace transformations) and shape factors to mathematically simulate adjoining walls.

Once a solution method is chosen and applied, the required surface area to dissipate the given heat can be calculated. It will be this surface area that will ultimately drive the size and weight of the enclosure by dictating whether fins will be required and, if so, what the size and shape of the fins shall be. If possible, the engineer should apply a reasonable safety margin to accommodate any simplifying assumptions and/or generalizations often made when performing hand calculations. However, it should be noted that this safety factor would likely be limited by the marketing needs to maintain an attractive industrial design, constraining weight and overall dimensions.

Next, a prototype of the enclosure will be produced and tested. The prototype should be as representative of the production component as possible — including material, geometry, weight, manufacturing process, etc. For this example, the production part will likely be die cast aluminum. Examination of the part geometry, including draft, wall thicknesses, complexity, etc. reveals the component to be an excellent candidate for a sand cast aluminum prototype. The prototype's thermal material properties will be very similar to the die cast production part. Power resistors that generate heat identical in magnitude and location to the actual circuitry can be attached to the prototype and energized. Thermocouples attached at strategic locations on the part can monitor and record the resulting thermal profile — verifying the design.

In the aforementioned example, the cost for the analytical analysis, prototyping and testing of the system would be in the range of $12,000 to $15,000. The time frame to complete this effort, including prototype leadtime, would be five to six weeks. At the completion of this task, the engineer would have definitive, empirical data from actual production representative hardware verifying that the design met the thermal requirements. Conversely, the cost to perform this task by numerical analysis could cost $18,000 and up. The leadtime would likely be six weeks minimum, and could run much longer depending upon the iterative process. And at the conclusion of the analysis, the results would still be theoretical, i.e., no physical model or empirical data would exist.

Nuclear Industry

The nuclear industry requires exhaustive analysis for their designs. These systems are typically large, complex and constructed of expensive materials. The process of nuclear product development and certification is quite different from that of consumer electronics. The issues of liability and long-term reliability far outweigh any rush to market. Performing an analytical analysis, prototyping and testing such a system is cost-prohibitive as well as potentially disastrous. Consequently, these systems are best suited for extensive numerical analysis.

When a nuclear power plant's fuel source has been depleted, the spent fuel must be properly disposed of in order to avoid environmental contamination. In many instances, the radioactive material is placed in a canister and stored at a secure location. The spent fuel is typically housed in a sealed, stainless steel cylinder and transported in a 55-gallon stainless steel drum packed with a glass-filled micro sphere composite concrete or polyethylene to provide shielding.

At it's final destination, the stainless steel cylinder is removed from the drum and placed in a concrete cask along with other spent fuel canisters. Industry standards require that the transport container be able to withstand a drop of 30 feet onto an immovable surface, a 30-minute transient fire test, and meet steady state thermal shipping requirements. Considering the potential liability of any catastrophic failure to the transport container, coupled with the expense, danger and difficulty of physical prototyping, this is an excellent candidate for numerical analysis.

The transient thermal test requires that the entire transport package be exposed to an 1,800°F open flame for 30 minutes to determine the maximum temperature gradient throughout the enclosure. This will determine if the elevated temperature will result in fuel leakage due to mechanical failure of the system. Because the shipping container is cylindrical, it is readily modeled within most numerical analysis software packages. Additionally, part symmetry allows the model to be further simplified by sectioning into fourths, reducing cost by lowering modeling and computing time. The deliverable will include tables, graphs and color fringe plots illustrating nodal temperature versus time.

For the steady state thermal analysis, the transient thermal model can be reused by modifying the boundary conditions. As with the transient test, maximum temperatures and thermal gradients can be shown in tables, graphs and color fringe plots.

The industry standard 30-foot drop test can be simulated in 3-D FEA software. These programs are capable of calculating complex nonlinear phenomena such as deformations, non-linear material behavior, collision related stresses and transient impact. Among the possible results is an animation of the drop, maximum stress values and plastic deformation in the part.

Deciding Factors

The decision to employ virtual prototyping (numerical analysis) or physical prototyping (analytical analysis with prototyping and verification) must be evaluated on a case-by-case basis. In many instances the complexity of the design and/or magnitude of the system and environmental requirements will be pivotal factors in this choice. Additionally, schedule, budget, in-house capabilities, risk, liability and resources all play a significant role in this determination.

In general, for less complex, lower liability systems that can be prototyped reasonably, the correct path is analytical analysis with prototyping and verification. For more complicated systems with high product liability that are impractical or impossible to prototype, a detailed numerical analysis should be employed. The correct decision at this initial juncture in the product development process will uncover and correct design flaws early and cost effectively — ensuring a seamless transition from design to manufacture and eventual product release. The development effort will produce a product that meets the design requirements, on time, and within budget. And that is cause for celebration.

TCT

*For more information contact **Bill Jennings**, president of Stone Mountain, Ltd. (Huddleston, VA) at (540) 297-6434, via e-mail at inquiries@stonemountainltd.com or visit www.stonemountainltd.com.*