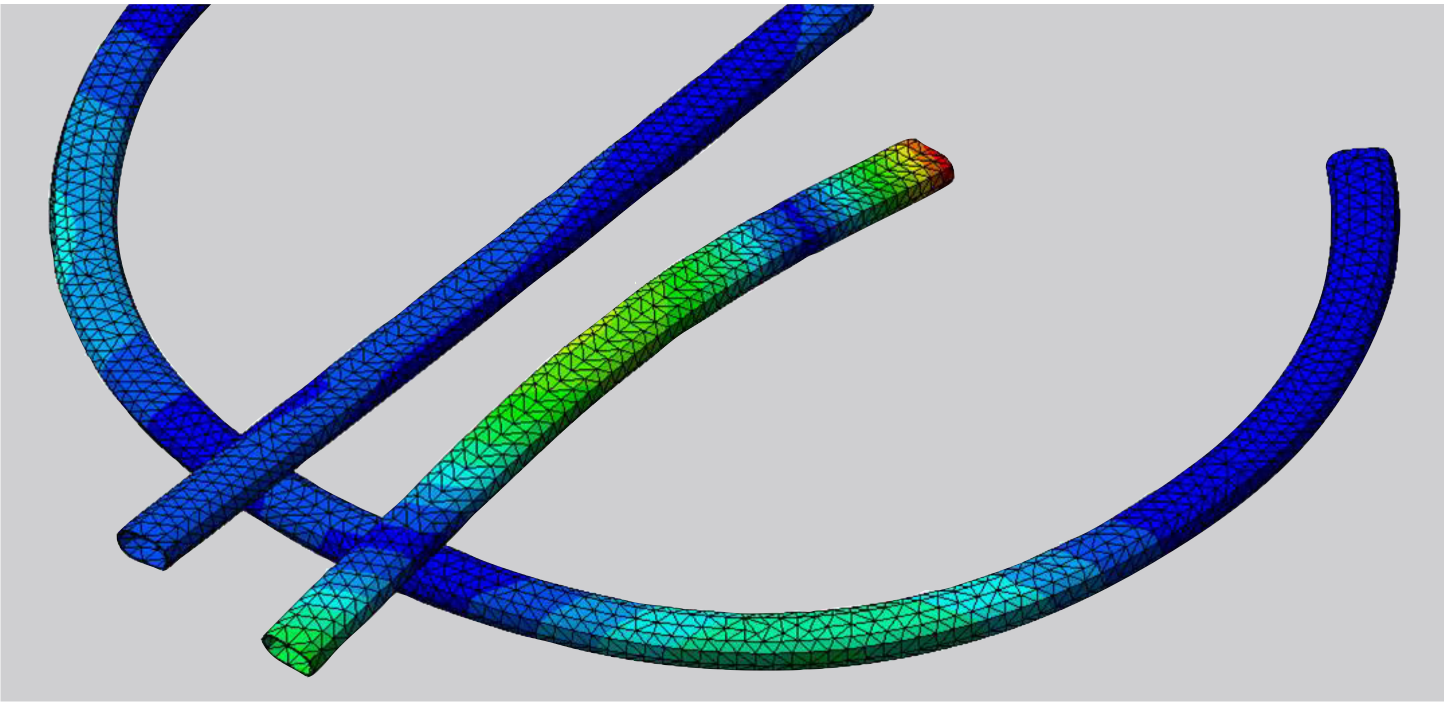
WHITE PAPER

INTEGRATING 3D MECHANICAL DESIGN AND ANALYSIS WITH PHYSICAL TESTING

Overview

SolidWorks software solutions make it possible for analysis and testing teams to work together in a closed-loop cycle, which allows your design team and company to reap multiple rewards. This article provides an overview of the traditional tasks in analysis and testing, and outlines options for you to close that loop. Through the use of detailed case studies we will prove the benefits of combining analysis and test data.



NATIONAL INSTRUMENTS™ SOLIDWORKS

Introduction

In the traditional design process of parts and assemblies, mechanical engineers produce models, analyze their behaviors under operating conditions, and pass physical prototypes “over the wall” for test engineers to evaluate in a pass/fail mode. Any problems that come to light are “thrown back” for design changes that, though necessary, come at the cost of additional prototypes and increased product development time.

If that wall could be broken down, with analysis and testing working together in a closed-loop cycle, both groups would reap the following benefits:

- Gain greater confidence in analysis results, supporting earlier design decisions
- Correlate test and analysis data to calibrate analyses
- Use test-based input values to drive improved analysis models
- Use analysis results to recommend sensor locations and test scenarios
- Result in a faster, cheaper, and better product development cycle

Integration among the tasks of design, analysis, and testing products is essential for creating such a collaborative environment.

Describing three types of vibrations

Factors in analysis

Once a solid model of a part or assembly has been created, the designer-engineer defines a set of boundary and operating conditions, then typically performs a finite element analysis (FEA) to identify the behavior of the part in response to those conditions. For example, in a static analysis, one could apply a given force and identify the resulting stresses; in a thermal analysis, applying a source of heat at a given location produces a distribution of temperatures across the part or assembly; and when fluid mechanics are relevant, an initial uniform flow can be influenced by both flow and thermal factors, with the analysis showing various graphical results such as expected velocities, temperatures, and pressures.

Two basic sources influence the accuracy of such analyses:

1. the mathematical algorithms and actual coding of the analysis software, and
2. the simplifications or assumptions made throughout the problem definition process, whether based on geometry or physics.

In recent years, enormous increases in the available computing power (especially at the desktop level) as well as the continuous refinement of FEA algorithms have combined to produce extremely reliable and capable analysis software packages. Thus, the main source influencing the accuracy now stems from assumptions made in determining the following parameters:

- Material properties
- Boundary conditions
- Geometry idealization
- Physics simplification, such as:
    - Flexible versus rigid behavior
    - Linear versus nonlinear behavior

Ideally, engineers would have continually improving sources of data on which to base the values for such input conditions.

Factors in mechanical test procedures
When designing test setups for a particular mechanical part or assembly, test engineers use best practices, years of experience, flexible hardware measurement systems, test and control software, and occasionally input from the actual mechanical designer to determine goals and methods. Typically, testing takes a pass/fail approach, verifying failure at some maximum load value or confirming in-spec temperatures at locations throughout a part.

If the measured values don't match with the predictions, it's back to the drawing board. Engineers build a revised prototype, the test department starts again, and another day, week, or month goes by. Moreover, it's difficult to tell if the test itself generated inaccurate data, since the following experimental parameters can lead to errors:

- Sensor locations
- Sensor & system calibration
- Sensor adhesion
- Sensor mass loading
- Test fixturing (free-free or constrained)
- Excitation or loading locations
- Load cycle

If test designers had better sources of specific information for choosing each of these variables, the test results would not only be more reliable, but also provide useful feedback to the designer to verify and improve the analyses.

Closing the loop between analysis and test

Today's designers and engineers often view analysis results directly on the original 3D CAD models. Results are displayed as color maps representing small changes; users can rotate, zoom, and select any point, then read its corresponding value (e.g., stress) across the model.

In the testing world, it's not as easy to look at the results and draw the corresponding level of detailed conclusions about physical behavior. For example, the output of a series of strain gauges is simply a stream of data, plotted as a set of superimposed curves on an x-y graph, with each curve tracking the measured values from a single sensor over time. An experienced viewer can pick out significant peak values or identify a trend of measurements from a subset of physically clustered sensors. However, it's still a challenge to sort out a hundred or a thousand sensors, and track them back to their corresponding locations on the physical model to fully understand their relevance.

Currently, both sides of this development scenario—the designer-engineers and the testers—generate the right types of data but present it visually differently. What if, instead, the test results could directly, point-by-point, help calibrate and verify the approach to the analysis? Real-world measurements and physical test data could provide improved material properties and better boundary conditions. Designer-engineers could compare an analysis with the test values to see when and where the analysis differed from the test. If a subset of values were quite off the mark, this might indicate, for example, that a nonlinear instead of linear analysis would provide a more accurate approach.

Conversely, what if trends in the analysis could help test engineers determine the best locations for sensors and decide where/how to place the proper loads? Overlaying test locations on a stress distribution model would better support decisions of where to place the sensors—targeting key expected stress points—instead of attaching them in a simple grid pattern that might miss local areas of unusual activity.

With this kind of improved correlation, each physical prototype would be based on a high-degree-of-confidence analysis, while each test run would efficiently capture precisely the data needed.

Integrated analysis/test examples

To move testing further up in the product development cycle—integrating test with design and analysis—four types of currently disparate information must be readily correlated: the 3D part geometry from the FEA mesh or the CAD model, analysis data, the physical location of each sensor, and the measured values taken from each sensor over time.

Test data is more sparse than FEA information, since the former comes from discrete sensor locations while the latter is integrated over millions of individual elements. A useful capability would be to interpolate between the sensors to generate test values for every physical point on the model at a resolution comparable to that of the FEA mesh. Then a color-shaded image would allow test engineers to "see" test data in the same graphic style as the analysis results, overlaid on the exact geometry, with animations showing behavior over time.

Since every node on the FEA mesh can have both a calculated and a measured value, correlated data sets would also allow the generation of error-map images comparing both values. Others in the company beyond engineering, such as manufacturing and the final customer, may find this information of interest. Putting all the data in a common, graphical form would make it easy to simply email such images as standard graphic files.

All of these needs are driving the development of an integrated test and analysis environment. Such a system would allow mapping test channels onto a 3D geometry model, then visualizing the measured results while readily comparing them to an analysis. Following are three examples of projects which successfully mapped these requirements into a common view, based on integrating software from Dassault Systèmes SolidWorks Corp. (SolidWorks® 3D CAD and analysis software) and National Instruments (NI).

Structural wing case study

A scale model of a simple aerodynamic wing was designed in SolidWorks 3D CAD software; locations were identified for mounting strain gauges across the surface (Figure 1).

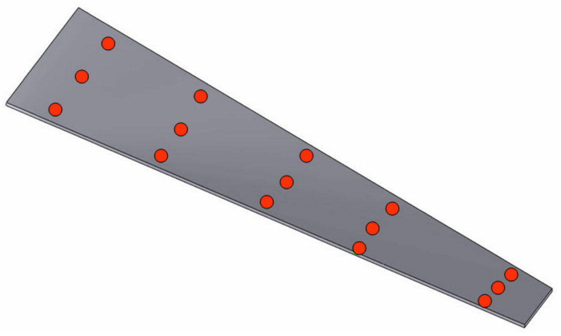


Figure 1: SolidWorks software model of simple aerodynamic wing with locations identified for stress test measurements

The wing was built out of aluminum and mounted in a test setup (Figure 2). Here it was clamped at its base (as on a fuselage) and subjected to a load along the tip. Boundary and loading conditions were the same as those chosen for initial software analysis conditions.

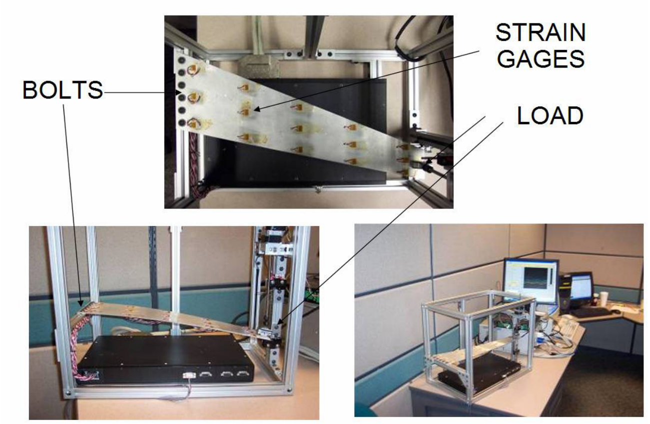


Figure 2: Physical test setup of wing, showing placement of strain gauges and loading mechanism corresponding to selected points in SolidWorks 3D CAD software design

The three-step process entailed first using SolidWorks Simulation analysis software within SolidWorks 3D CAD software to determine stresses across the wing. Designer-engineers meshed the geometry and performed a structural analysis, and the software automatically generated stress color maps (Figure 3).

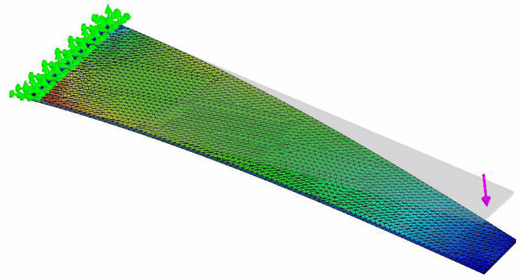


Figure 3: SolidWorks Simulation meshed wing geometry and resulting structural analysis results

Secondly, the corresponding physical testing employed NI LabVIEW test software to control the tip's loading and record measurements from strain gauges mounted across the wing's surface.

The third step, graphically and numerically correlating the analysis and test data, used NI INSIGHT software, a companion to NI LabVIEW. NI INSIGHT read in the software-based mesh geometry, the SolidWorks Simulation analysis results, and the NI LabVIEW test-channel data. It then mapped the test channels onto the wing geometry at the sensor locations of the strain gauges, and compared the test results to the analysis results (including differences) all in one view (Figure 4).

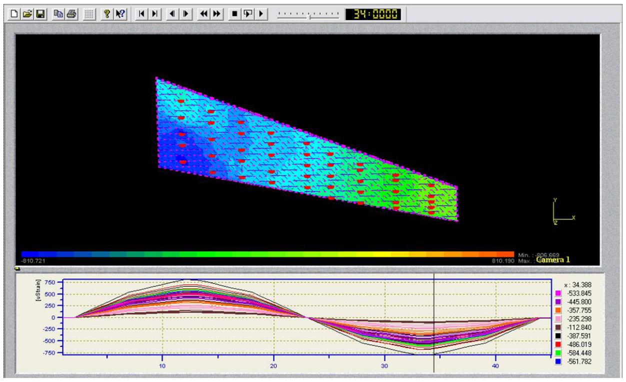


Figure 4: NI LabVIEW test data mapped onto SolidWorks software geometry and SolidWorks Simulation mesh using NI INSIGHT

In addition, more detailed comparisons could be made by viewing various aspects of the graphical data in simultaneous windows. Figure 5 shows the test data on the top left, the analysis on the top right, and the differences below as both a percentage difference and the actual difference to help highlight variations in expected and actual values.

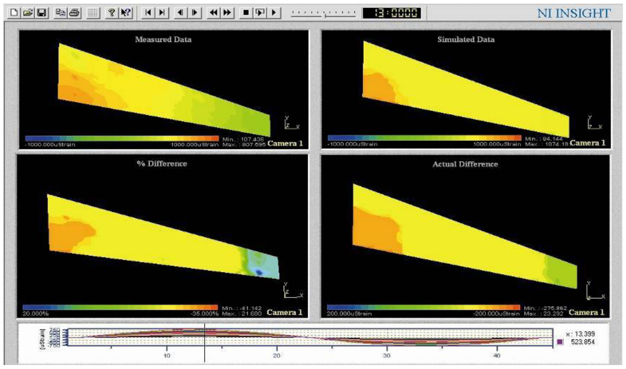


Figure 5: Structural test and analysis of loaded wing behavior correlated in NI INSIGHT

Within this single graphical environment, all members of the product design team are able to extract information as needed. SolidWorks Simulation users can take the correlated information directly from NI INSIGHT and use it to improve the chosen analysis parameters. (In this wing experiment, the measured maximum tip displacement of over two inches across a 20-inch wing span convinced the designer-engineers they needed to switch to a nonlinear FEA approach.) The NI LabVIEW test engineer might recognize an outlying value as indicating that a glued sensor came partially loose. And for a designer in SolidWorks software (who doesn't use analysis), NI INSIGHT would still map results back onto the CAD geometry, highlighting any areas of concern that might warrant physical design changes.

A variation on this example that could be performed using computational fluid dynamics (CFD) software, such as SolidWorks Flow Simulation, would involve measuring pressure distribution instead of stress across the wing surface; wind-tunnel measurements with the wing fixed at different angles of attack would help identify the critical stall angle of this particular design. Moreover, by viewing the test results on the 3D geometry using NI INSIGHT as they happen in real time, users could choose to simply stop the test when a certain condition is reached (e.g., stall), or if it's headed in the wrong direction.

Thermal plate case study

In a second example, the system under test was a simple rectangular aluminum plate. The question was how well the designer-engineers could model heat flow across the plate as induced by two 212 °F heat sources placed on the upper surface (Figure 6) and monitored over a period of five minutes.

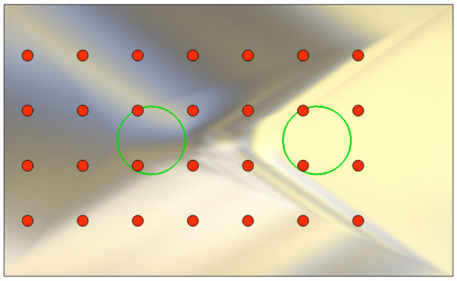


Figure 6: SolidWorks software geometry of thermally insulated plate, with locations marked for attaching thermocouples

Thermocouples were attached to the underside of the thermally insulated plate according to the SolidWorks software geometry. Their wires were connected to NI signal conditioning and data-acquisition (DAQ) hardware controlled by NI LabVIEW software (Figure 7). For each of the thermocouples, the test team recorded the data stream from the physical set up once per second, for a 300-second time span.

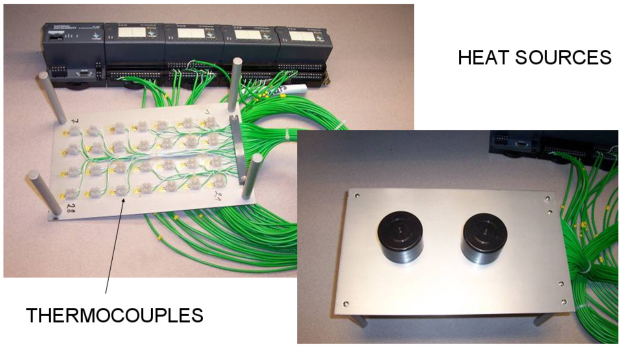


Figure 7: Thermal example—aluminum plate with dual heat sources; thermocouples placed according to layout in SolidWorks software design and controlled by NI LabVIEW software

Designer-engineers used SolidWorks Simulation to analyze the transient thermal response (conduction) across the initially room-temperature plate (Figure 8).

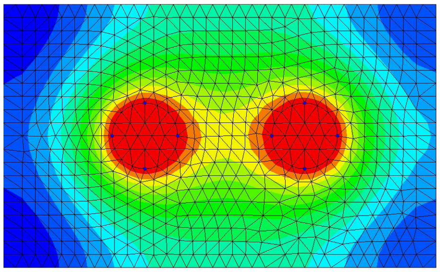


Figure 8: SolidWorks Simulation transient thermal response across aluminum plate geometry, when heated with dual sources

Using NI INSIGHT, the product group brought both the analyzed and measured data into a single environment where the results could be visually compared on the SolidWorks 3D plate geometry (Figure 9). The measured data was interpolated to the same resolution scale as that of the thermal analysis. NI INSIGHT also allowed viewing the results across time slices, such that anomalies in both location and time intervals could be easily identified.

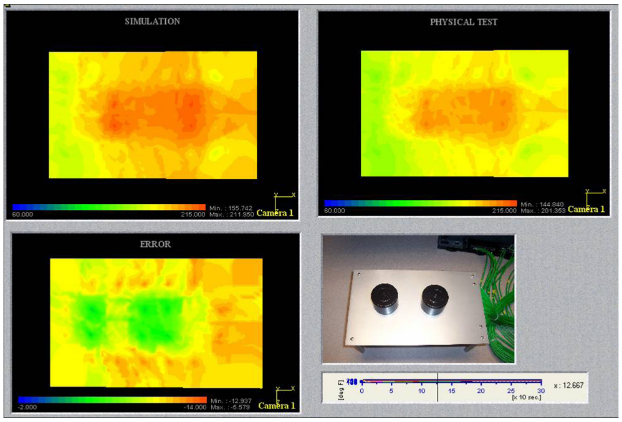


Figure 9: Thermal test—correlation of simulated and measured temperatures on heated plate within NI INSIGHT

While the temperature distribution pattern across the plate over time is similar between the analysis and the physical test, there is absolute error between the two which can be easily visualized. The higher error evident towards the outer edges of the plate could be traced to stronger convection and radiation effects towards the periphery that are not modeled in the analysis, which only takes into account conduction. If required to reduce the error, the analysis could be re-run with these effects included.

Vibration mode shape case study

A third example of coupled analysis and test data involved identifying mode shapes of a vibrating, near-circular test structure. Modal frequencies and mode shapes are commonly evaluated for most structures operating in a dynamic environment such as an automobile or in industrial machinery. The main concern is that the structure may vibrate excessively which may cause it or other adjacent parts to fail prematurely.

Vibrations may also transmit to other parts of the structure affecting the perceived quality of the system, e.g., engine vibrations transmitted to the driver. The historical challenge in doing vibration testing is that in addition to requiring very expensive measurement systems with high accuracy (24 bit) and high sampling rates (greater than 100k samples/sec), the short dynamic nature of the event requires that measurements at all the sensors (accelerometers) be synchronized and sampled together.

Where to place the sensors is another open issue. Putting a sensor at a primary node of the system essentially wastes that sensor as its registered displacement and acceleration will be zero. Further, one typically uses a trial and error process of exciting the structure with a force hammer at various locations in order to capture all the modeshapes. Often the test engineer does not know whether the tests have been successful until all the data has been analyzed offline, possibly several days later. If the mode shapes have not been sufficiently captured, the tests need to be redone. Lastly, the test design must account for mass loading from the accelerometers, since this factor can often distort the test results for light or hollow structures. Usually, the density of sensors is sequentially reduced to reduce the effect; unfortunately, this also reduces the amount of test data captured.

In the example, the unit under test was a hollow aluminum 50 cm diameter wheel in the shape of the euro symbol (Figure 10).

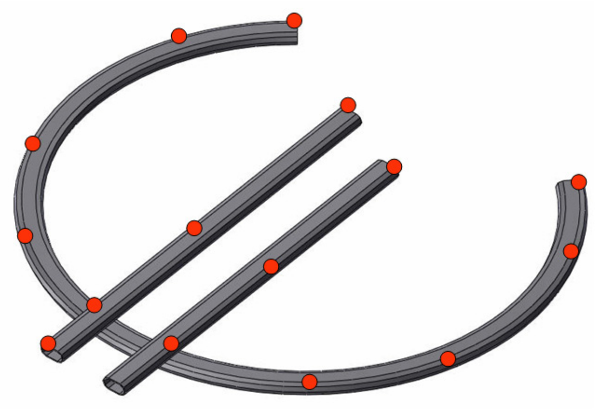


Figure 10: SolidWorks software geometry of aluminum euro-symbol unit for vibration testing, showing suggested accelerometer sensor placements

The structure was fixed at two locations but otherwise free to vibrate. To record the shape of the vibrational response, accelerometers were attached around the rim and along the parallel bars, then connected to the appropriate NI dynamic signal acquisition (DSA) devices on the PXI (PCI eXtensions for Instrumentation) platform (Figure 11).

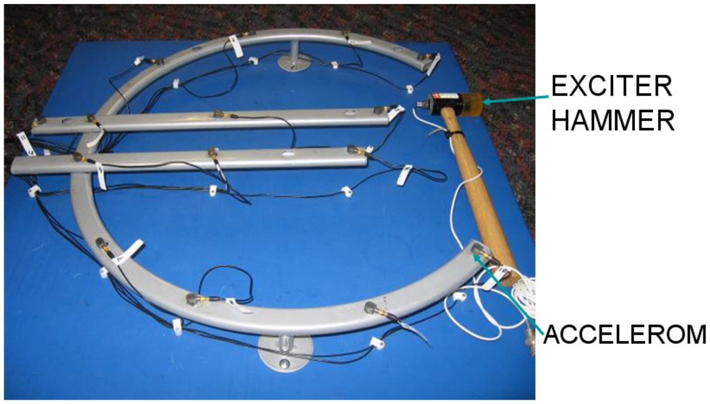


Figure 11: Aluminum "euro" structure mounted for vibration mode testing, with sensor placement according to SolidWorks software geometry

Designer-engineers had analyzed the same structure in the identical constrained mode for the natural frequency response in SolidWorks Simulation (Figure 12), analogous to a shaker-table test.

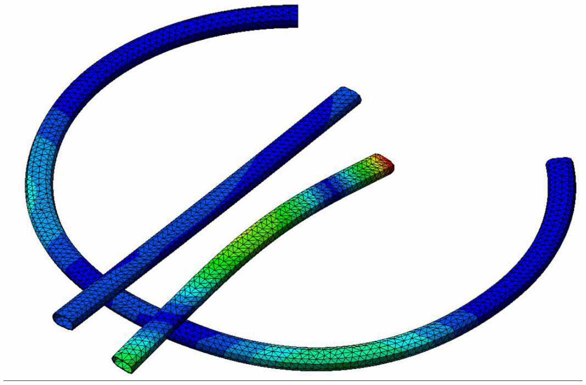


Figure 12: SolidWorks Simulation analysis of euro-shaped aluminum structure

An instrumented force hammer was used to excite the structure at the free end of the shorter straight cross-bar; the response at all the accelerometers was recorded over 100 milliseconds, at a sampling rate of 10,000 Hz, until the vibrations had died down. The accelerometer data was recorded and analyzed by NI LabVIEW Sound and Vibration Toolset and transformed from the time domain to frequency domain for easier analysis.

The resulting normalized modeshape of the structure was brought up in NI INSIGHT, side-by-side with the SolidWorks Simulation analysis results and the comparable normalized test values interpolated from the sensors. The animation option generated the mode shape.

Given the highly dynamic nature of the event, this ability to map test data to the geometry and having it deform accordingly allows easily visualizing the test mode shape, a task which would otherwise only be possible with a very expensive high-speed camera. Again, the differences between test and analysis were readily displayed in the same view, along with a simple camera-image of the device under test for comparison (Figure 13), which could be used to calibrate and improve the analysis prediction.

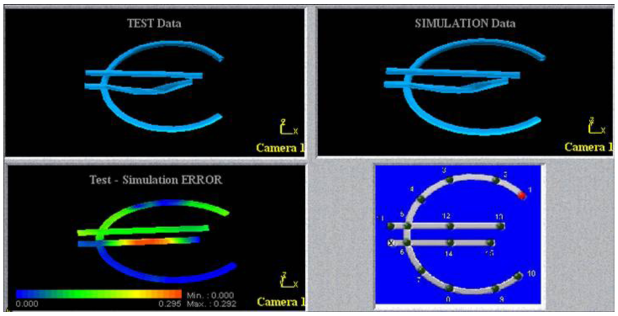


Figure 13: Vibration of euro-shaped aluminum structure—correlation of measured and simulated mode responses

The analysis results helped guide the test engineers not only to optimize the sensor locations but also to change the placement of the excitation strike.

With regard to sensor mass loading, an elegant solution is to model the accelerometer masses in the analysis, and then calibrate the mass-loaded analysis with the similar mass-loaded physical test results to improve the analysis fidelity. Once that has been accomplished, the accelerometer masses can be unloaded in the analysis (which is not possible in the physical world) and the true modal frequency and modeshape predicted without mass loading.

This approach is only possible by integrating the analysis with the physical test—neither analysis nor physical test alone can accomplish the task, which further points to the real value that integration brings to the table.

Design validation for integrated motion controls

Another area that could benefit from feedback between software analysis and actual testing is control-system design, whether in mechanics, thermal, or fluid-solid systems. For example, today's high-speed electromechanical systems often include a servo-driven actuator that must operate with microsecond response times. Incorrect motion control configuration settings such as PID (Proportional, Integral, and Derivative) gain parameters can lead to large settling time or excessive over- or undershoot, resulting in suboptimal performance.

In addition, incorrect parameters or sequencing in motion control commands may result in collisions causing extensive damage to hardware. Such problems are most apt to occur when a controls engineer devises the logic control parameters without detailed input from the mechanical engineers who created and fully understand the behavior of the structure being controlled, often called the "plant."

If the motion dynamics of the plant could be analyzed, accounting for forces, friction, gravity, mass, or thermal inertia, etc., this information could be fed back to the controller analysis to improve the corresponding control parameters and commands that affect the motion dynamics. With such an integrated system, users could:

- Develop control programs for programmable logic controllers (PLC) or advanced programmable automation controllers (PAC) based on virtual assemblies.
- Visualize the assembly motion with graphics, identifying and thus avoiding collisions and over- or undershoots.
- Make design changes to both the controller and the plant structure early in the development process to optimize performance.
- Reduce the risk of damaging the actual machine during start-up.
- Result in a faster, cheaper, and better product development cycle.
- Start training and documentation earlier in the manufacturing cycle.

This design validation capability now exists through the combination of the SolidWorks Motion dynamics analysis feature and NI LabVIEW Control Design along with the NI SoftMotion Development Module software for motion controller analysis. SolidWorks Motion helps simulate mechanism motion by taking into account mechanism dynamics, such as forces and friction, and generates such information as position and kinetic energy.

NI LabVIEW with NI SoftMotion helps simulate a complete custom motion controller with functions such as trajectory generation, spline interpolation and control algorithms such as PID. The first round of control parameters calculated in NI LabVIEW is fed back to SolidWorks Motion to verify how the plant will react to that stimulus, and, depending on how large the feedback error is, the control parameters are continuously tuned until acceptable system performance is reached.

Such closed-loop analysis between mechanical motion and control development environments can help drive design decisions for both the mechanical and controller aspects of the design. For example, engineers may choose to replace a ball-screw stage with a linear motor when they discover the given load cannot be moved at the rate they want. They also can check for mechanical interference in the system, accounting for loads on the system and the control algorithm used. On the control side, engineers may choose to use PID with velocity feed-forward instead of regular PID to achieve better control. They also may want to replace PID with fuzzy logic or Model-Free Adaptive control for controlling nonlinear or higher-order systems.

This was the case with a system that drove a two-axis mechanical stage in a circle. Determining the motion commands with the correct parameters was critical to avoid damage; in addition, minimizing the settling time was a requirement for optimal performance. Position values calculated from SolidWorks Motion became feedback input for refining the motion controller commands in NI LabVIEW, without any trial-and-error risk to the physical hardware (Figure 14).

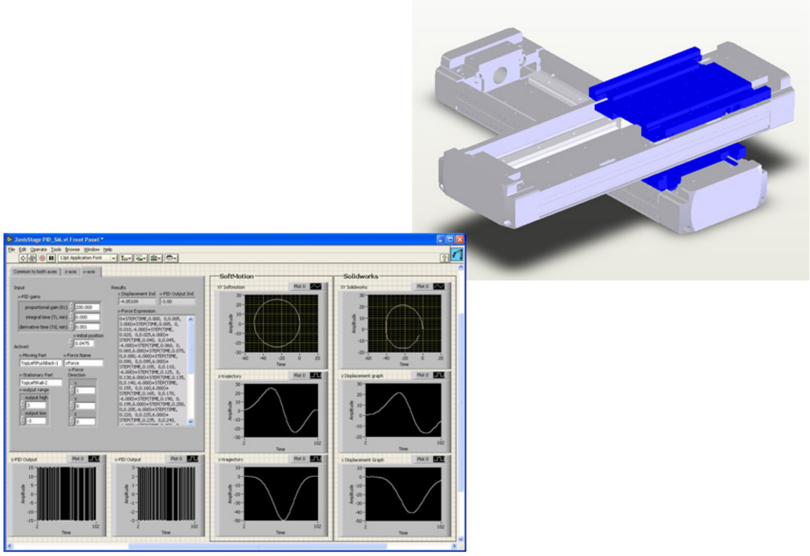


Figure 14: Motion-control coordination for a two-axis stage

Conclusion

Tightly integrated physical test and analysis software provides the following benefits impacting the full lifecycle of product development:

- Greater confidence in analysis results to make design decisions earlier
- Ability to run efficient tests by simulating them in advance
- Optimized investment in both test and analysis
- Reduced number of physical prototypes due to leverage of combined test and analysis, and reduced damage to prototype hardware during control system development
- Feedback assistance for designers not experienced in the nuances of analysis
- Faster, more cost-effective product development cycle

Using analysis results to refine tests, and using test data to improve analysis models, offers a win-win approach to increasing company-wide productivity and gaining a competitive advantage in the marketplace.

Dassault Systèmes
SolidWorks Corp.
300 Baker Avenue
Concord, MA 01742 USA
Phone: 1 800 693 9000
Outside the US: +1 978 371 5011
Email: info@solidworks.com
www.solidworks.com