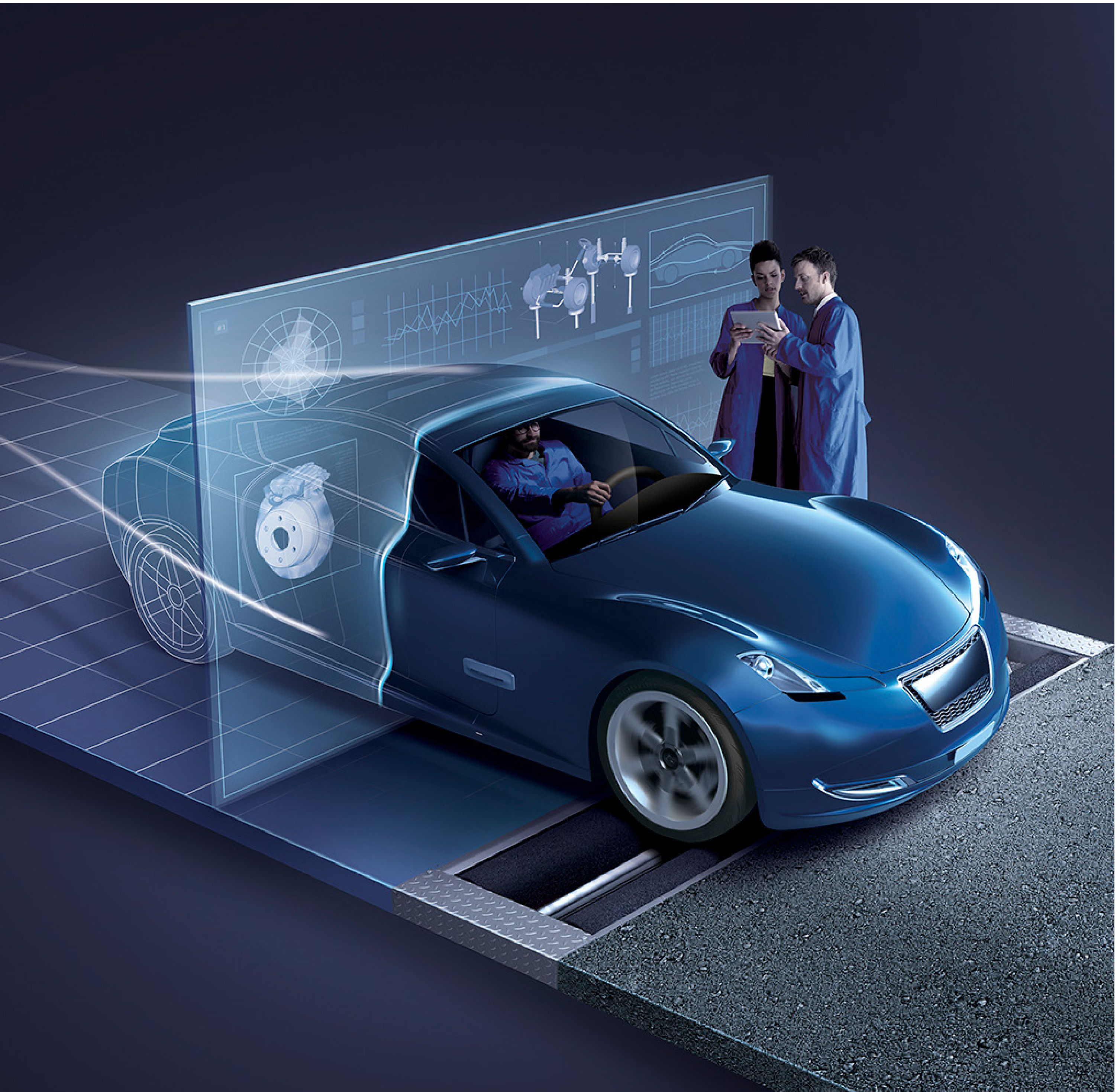
DRIVING INNOVATION WITH REALISTIC SIMULATION

VOLUME 2



Driving Innovation with Realistic Simulation

Content

Leveraging Realistic Simulation for Global Validation, Proven Performance

HOW DO INDUSTRY LEADERS DRIVE INNOVATION, OPTIMIZE PERFORMANCE, AND REDUCE WARRANTY & RECALL RISKS?

With innovation as a continuing driving force for how companies increase their competitive advantage, many OEMs and automotive suppliers are taking a holistic look at how they can streamline their product development. Improving vehicle performance and quality not only helps save cycle time and reduce costs, it also increases innovative capacity.

Leading automotive companies are gaining strategic competitive advantages by adopting simulation solutions that free up valuable time & resources to innovate better vehicles. These solutions support better testing, virtual and physical prototype management and enhanced verification & validation to greatly increase product performance and quality.

Volume 2 of this eBook series explores how automotive OEMs and automotive suppliers adopted Dassault Systèmes' **3D**EXPERIENCE® platform and its Global Validation, Proven Performance industry solution experience to increase their designers innovative capacity. By integrating realistic simulation into their processes, these leaders have enhanced product quality, saved cycle time and reduced development costs:

Dana's Engineers Team Up to Accelerate Product Design with Simulation Lifecycle Management

Major automotive supplier realizes up to 25 percent time-savings in their computer-aided engineering projects

The recent revival of the U.S. automotive industry is a success story on many levels. Bridge loans granted by the government enabled some automakers to restructure. Tightened fuel-economy and pollution standards spurred new R&D. An improving economic climate released pent-up demand for new cars—and this time Detroit was ready with fuel-efficient, eye-catching models that brought buyers back to the showrooms. The Big Three (Ford, GM and Chrysler) were on the path to recovery.

As the automakers' business picked up again, so did that of their suppliers. Dana Holding Corporation—a U.S.-based, Tier 1 global supplier of axles, driveshafts, sealing and thermal-management products, off-highway transmissions, and service parts—saw a strong turnaround in revenues and margins. While their customers' recovery was certainly a major contributor to these results, credit for Dana's rebound also goes to an evolution in mindset that helped keep the company on track through tough times.

"We underwent a cultural change at Dana from a mainly cost/manufacturing-driven company to an engineering-driven one," says Frank Popielas, senior manager of advanced engineering in the Dana Power Technologies Group and head of CAE (computer-aided engineering) for Dana. "This meant a shift in focus, from how to control costs and manufacture efficiently, to how to innovate. Obviously all these need to be integrated. But if you focus solely on costs, product quality will go down. As an engineering-driven company, we look at how to improve a product from a quality and function perspective. Innovation, supported by the right engineering tools, made our company more competitive."

Many automotive suppliers struggled during the recession, and unemployment rates rose. However, since Dana had already developed substantial in-house CAE and high-performance computing (HPC) resources, the company made a point of retaining their design engineering teams. "During the downturn, we kept our focus on CAE," says Popielas. "We knew that, in the long run, the investment would be worth it."

Engineering return-on-investment with CAE

Indeed, CAE has proved invaluable to the company. Dana's products include a vast range of gaskets (cylinder head, exhaust, intake manifold, etc.), cam covers, and heat exchangers; mechanical and electrical components; driveline components and assemblies (axles, driveshafts, gear boxes, etc.) and more. Materials range from metals to rubber to plastics to fiber-based. Production processes include casting, injection molding, heat treatment, forming, magnetic pulse welding, etc.

"Because we make pretty much everything around the automotive powertrain and drivetrain, our portfolio involves huge complexity," says Popielas. "To ensure quality when designing our products, we need to look at everything that can impact them, including stress, strain, fatigue, molding,

Figure 1. Founded in 1904, Ohio-based Dana now has 24,000 employees in 26 countries. The company's global brands include Spicer drivetrain products, Victor Reinz sealing products and Long thermal products.

Source: SIMULIA Community News

gas, oil and cooling flow, air and oil separation, thermal distribution and, of course, their complex interactions. CAE is the toolkit that supports the development of our products in the engineering space. Simulation enables us to verify and validate—virtually—product functionality."

While real-world testing remains the ultimate proof of that functionality, Dana's extensive use of CAE has enabled the company to do less and less physical testing in recent years. "Simulation speeds up the product development process, captures data that can be used to optimize the product and gives our engineers more freedom to innovate," says Popielas. "Innovation is critical for us, but it still has to be cost-effective. Our CAE resources help minimize, or even neutralize, many time-consuming tasks of the past, such as creating drawings, prototyping, and going through extensive physical testing for each design iteration. CAE takes out costs across the board for us."

Dana's CAE arsenal is extensive (see Figure 2). Among the tools are Abaqus from SIMULIA, Dassault Systèmes, the company's longtime finite element analysis (FEA) solver for realistic simulation; Hypermesh from Altair, Abaqus/CAE and Simlab for preprocessing; StarCCM+ from CD-adapco and FlowVision from Capvidia for computational fluid dynamics (CFD); MoldFlow for molding simulation; and fe-safeTM for fatigue. Isight, also from SIMULIA, is used for optimization tasks such as Design of Experiments (DOE).

While continuing individual component analysis, Dana has also made the step into simulating subsystems, complete systems, and global models. "As the company transitions to full systems engineering in the virtual world, we expect to add even more software codes in the future," says Popielas.

Helping CAE tools work together with Simulation Lifecycle Management

As the simulation process at Dana matured, the challenge for the engineering group shifted from how to accurately predict real product performance, to other pressing issues: How to more effectively connect simulation with the rest of the business and decision making processes. How to improve collaboration with both the customer and among Dana's global engineering resources. How to improve the management of the growing volume of data generated by the simulation process, the approaches and the IP created by the CAE analysts.

To address these needs Dana turned to Dassault Systèmes and the SIMULIA Simulation Lifecycle Management (SLM) solution. Dana engaged in an in-depth evaluation of SLM to measure capability to their specific needs, and began deploying SIMULIA's SLM in the summer of 2012. Based on Dassault Systèmes' 3DEXPERIENCE Platform technology,

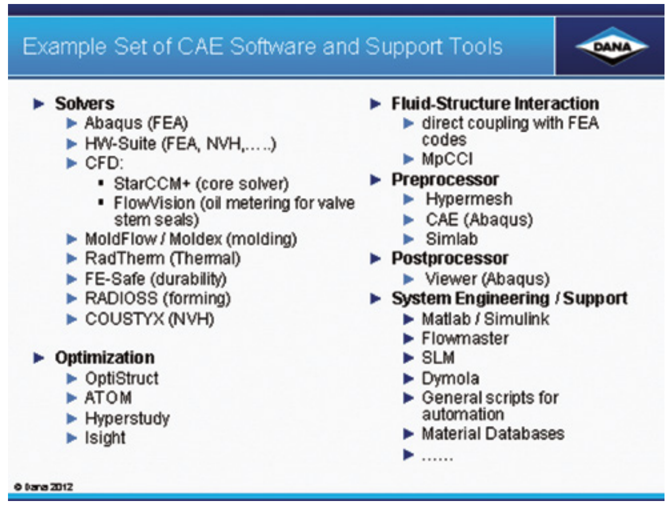


Figure 2. Sample set showing the variety of different CAE software programs Dana uses for simulation during the design and development of its products. The company's deployment of SIMULIA SLM provides an open environment supporting multiple technologies so they can use applications that best support their needs, as well as collaborate with internal teams, customers and their own suppliers.

SLM enables a company to define and manage simulation methods, models and procedures (scenarios). "When you get into virtual engineering, in order to not waste your investment you have to have a tool in place that manages data, process and development," says Popielas.

Historically, CAE at Dana was the purview of individual experts who would select from among multiple software tools to perform everything from design data preparation to simulation execution to results analysis, storing both inputs and solutions mostly on their local hard drives. This made collaboration difficult, and coordinating larger projects a major challenge. Communication about design changes was also an issue, with the experts sometimes running simulations on outdated data files. The situation was further complicated by Dana's growth strategy of dispersing teams globally in order to keep closer contact with their geographically diverse customers.

"An individual product validation can involve thousands of gigabytes of information over time," says Popielas. "When you generate as much data as we do, especially in the form of such complex simulations, you need to be able to assess what you have, know where it came from, and track it over time. SLM is enabling us to do all of that."

As they began deploying SLM, Dana took a "bottom-up" approach that helped the process evolve logically. "This was not a top-down, enterprise-wide deployment," says Popielas. "We considered all the different processes we wanted to connect via SLM and looked at where it made sense to start."

Source: SIMULIA Community News

An important aspect of the implementation process has been the creation of guided templates within SLM that capture best practices and standard method for simulation work on core products. A next step Dana is working on is the creation of fully automated templates. "These standardized templates are in the front end, with data loaded by non-CAE engineers and simulations running in the background," says Popielas. "Our users don't need to have knowledge of the specifics of the CAE software they are using, just access to a menu of proven shortcuts that help them accomplish their goals. If additional information is needed during the course of a product validation, they can use SLM to quickly locate input from our physical test labs. This automation enables future fully virtualization of engineering as it is being implemented in all areas."

As deployment proceeds throughout Dana, Popielas says, "SLM is helping us manage everything so much more effectively. We can easily store data and find it again, literally saving weeks of searching. In the past we wasted a lot of time hunting for information. SLM is not just archiving, it's an environment where you always have working access to all the information you need."

Openness and live visualization are key to collaboration

In the future, SLM's open platform will also allow the Dana team to share and exchange relevant data—among themselves, with their automotive customers, and with their own suppliers. "Our user base is very diversified," says Popielas. "We need to be able to work with any software tool out there. Within SLM we easily generate connectors through which we can line up to the different software packages, which can be CAE tools, a PDF, or even an internally written script, anything with an executable."

SLM process management capabilities make such teamwork smoother by providing consistency and repeatability. "We're seeing 20-25% time savings over our previous methodology," Popielas says. "We can more readily identify the 'sweet spot' for cost-versus-performance that generates profitability."

As all this complexity runs automatically behind the scenes, what the Dana teams appreciate most is the visual interface everyone works from when accessing SLM: Live Simulation Review, which is based on Dassault Systèmes' 3DLive platform [see Figure 3]. The user sees an onscreen turntable, on which sit 3D representations of the various jobs in progress on any given part or assembly. By clicking on a particular image, the user can identify and navigate to all relevant simulations being worked on by whoever is involved in that particular aspect of the product's development. As the user performs whatever tasks are required that day, all changes (and their history) are updated automatically, and are accessible to

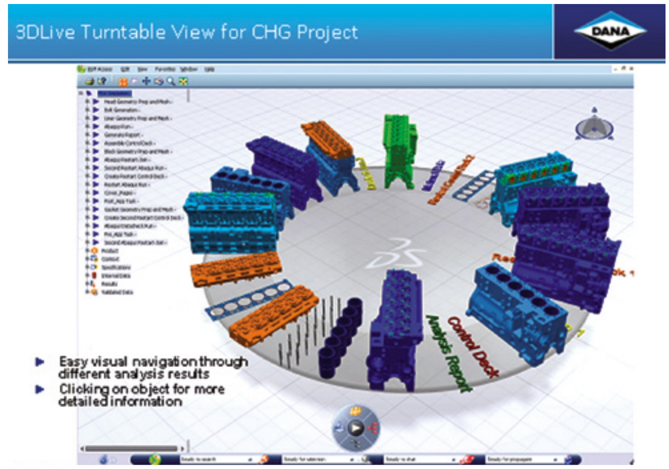


Figure 3. Live Simulation Review screenshot of a cylinder head gasket (CHG) project shows the turntable format in SLM (from the Dassault Systèmes SIMULIA application) through which users can access all aspects of a product development project and collaborate with remote teams in real time.

everyone authorized to access the project. Remote teams can all be on the (user secured) Live Simulation Review in order to collaborate, in real time, on model development.

"This is where I think SLM is the leading technology on the market," says Popielas. "The methodology goes hand in hand with what I like to call 'iCAE™.' The understanding of the importance of collaborative computer-aided engineering is deepening as the use of simulation becomes increasingly widespread throughout industry. If you want to draw a lot of different disciplines into the engineering space together, you have to provide a virtual environment that is visually intuitive. The ability to collaborate this way is a key reason why we went with SLM."

The future potential of "iCAE™"

Full implementation of SLM at Dana is expected to be complete in the near future, and the company's engineers are already anticipating how the software will enable them to further their exploration of the potential of iCAE™.

Upcoming enhancements include deploying templates into engineering spheres such as manufacturing. "We want to integrate manufacturing steps into simulation," says Popielas. "Understanding the physics of the production process will further improve product quality, as will optimizing the layout of manufacturing stations." The remote visualization offered by cloud computing is still on the horizon, notes Popielas, but many benefits of iCAE™ are already available. "When you start taking advantage of these technologies, you have so much to gain," says Popielas. "We are talking double digits, always. It's extremely cost-effective when you do it right."

Source: SIMULIA Community News

Honda Leverages Simulation to Meet Changing Market Needs

The automobile market is in a period of great change, with factors like environmental conservation and rapid market growth in developing countries now coming into play. Model-based development (MBD) is advocated as a development process that can support these changes. The previous leader of engine development for the Honda F1 Team, Kazuo Sakurahara, is currently involved in the creation of a new development process for mass-produced vehicles at the Honda R&D Co., Ltd. Automobile R&D Center. Sakurahara spoke to SIMULIA Community News to discuss how Honda uses computer-aided engineering (CAE) and the steps it has taken toward MBD.

SIMULIA Community News (SCN): What kind of effects have changes, such as environmental issues and rapid market growth in developing countries, had on the development workplace?

Kazuo Sakurahara: Speed is everything. Automobile manufacturers need to increase the rate of their development to the point that they can handle whatever changes arrive next, or they are not going to survive.

SCN: How are you increasing the pace of development?

Sakurahara: We strive for a process that makes full use of CAE, aiming to allow for optimization of functions and measurement parameters at an early stage of advanced development. We want to ensure that the development of the hardware skeleton is already complete as the vehicle goes into the development for mass production. MBD will heighten competitive power in comparison with the old experiment and experience-based process.

SCN: Why is Honda focusing so heavily on the use of simulations (CAE)?

Sakurahara: We want to avoid building prototypes. It takes an awful lot of time to build something and then test it. We want to take it to the level that you only have to build something as the final check. For this reason, we desire greater accuracy from our CAE.

SCN: In the development process, how are you making use of CAE?

Sakurahara: At the stage of the advanced development prior to the development for mass production, in the process of selection of specifications and basic design, the designer carries out CAE using CATIA Analysis in order to check and optimize the specifications. In the detailed design process, the quality of prerelease designs is evaluated using CAE. Areas that are highly integrated and require a lot of time, like nonlinearity and vibration noise, are performed by specialists using Abaqus Finite Element Analysis (FEA).

SCN: What has enabled designers to apply CAE more widely for themselves?

Sakurahara: The evolution of CATIA is largely to thank for that. The fact that the mesh in CATIA can be generated more easily than before is a really big factor. The time it takes to generate a high-quality mesh is vital when it comes to using CAE. Furthermore, using optimization tools like Isight greatly reduces the amount of work and time CAE takes, and that's another way in which we are seeking to increase the range of design CAE.

SCN: When do you use Isight?

Sakurahara: Take, for example, the engine. There are all sorts of conflicting requirements—it needs to be as light as possible but strong, to be quiet without too much vibration, yet sufficiently powerful—and you have to find a tradeoff. The existing manual process involves adjusting the model, carrying out CAE, and making a judgment, then repeating this process over and over. In the new workflow, Isight processes numerous design iterations without user intervention, changing the shape of the parametric model automatically during CAE and finding the best possible shape for us.

SCN: With the expansion of applications for CAE in the design workplace, there have been lengthy debates concerning the importance of analytical precision. What do you think about the precision of CAE evaluation?

Source: SIMULIA Community News

Sakurahara: For Honda, if you include every degree to which evaluation can be performed, from complete evaluation to relative evaluation to determine a general policy, we are able to utilize CAE effectively for about 70% of the applications where we would like to do so.

SCN: What do you believe needs to be done to improve evaluation and achieve greater accuracy?

Sakurahara: What is important here is to note that Calibration & Evaluation is seen as "tests to increase the accuracy of simulations." This means that many more tests are required than if they were just being performed to evaluate simply whether or not the requirements of the design had been fulfilled. It takes a lot of work, but this is necessary in order to increase the accuracy of the physical model that is the start of development using MBD. Feeding the statistical model obtained from the results back into the physical model allows the simulations to come closer to the real world and, in turn, allows greater precision at the start of development. At the moment, the process often goes back and forth between basic design and detailed design, but we want to reduce the need to go backward by increasing the accuracy of the physical model.

SCN: How is this different from the comparison between CAE and experimental results that have been used until now?

Sakurahara: Evaluation using simulations has been about whether or not, under certain specific and limited conditions, the experimental results fit. So, no matter how accurate the results for a certain specific engine, there is no way of knowing

whether the results are accurate for a new, totally different engine. In order for us to use MBD in the future, we need to work to feed the experimental results for all the vehicles we develop back into the physical model. In the initial phase, this will increase the number of experiments performed, but as accuracy continues to increase, the number of experiments required will naturally decrease. Organizing this process and building it into the development flow is vital.

Source: SIMULIA Community News

Eaton Ensures the Reliability of Critical Supercharger Components with fe-safe

Powering business worldwide

Eaton is a power management company with 2013 sales of $22.0 billion. Eaton provides energy-efficient solutions that help customers effectively manage electrical, hydraulic and mechanical power more efficiently, safely and sustainably. Eaton has approximately 103,000 employees and sells products to customers in more than 175 countries. Because of the pivotal role Eaton plays, Eaton is committed to creating and maintaining powerful customer relationships built on a foundation of excellence. From the products it manufactures to its dedicated customer service and support, Eaton's automotive businesses play an important role in the global automotive industry.

The innovation strategy at Eaton aims to meet an ever-increasing list of customer and regulatory challenges, from design and aesthetic choices to demands for improved performance and efficiency. Supercharger technology is a key part of this strategy: on small engines the aim is to boost performance whilst keeping fuel consumption low, and on larger engines the objective is to achieve higher acceleration for a given engine size. Eaton superchargers are used by many of the world's leading automotive OEMs, including Audi, Ford, GM, Mercedes-Benz, and Volkswagen.

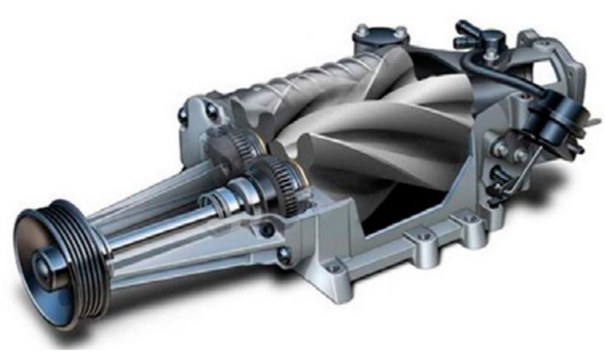
Quiet and reliable

In the past, superchargers have been known to produce noise. One source of noise stems from the pressure pulsations that occur as the lobes of the pump mesh and un-mesh during boosted operation. Another source of noise occurs during un-boosted operation, e.g. when the car is stopped and the engine is idling. In this case, vibrations produced by the normal combustion of the engine can be transferred through the belt and cause gear rattle in the supercharger. In a race setting, these various noises are at most a nuisance, but in passenger cars they can be perceived as a lack of quality or perhaps even a more significant problem with the engine itself. To meet these challenges, Eaton has invested considerable engineering resources to develop the world's quietest and most reliable superchargers, and has realized innovations in both reducing the original sources of noise and improving noise isolation.

Noise isolation

One approach that Eaton uses to isolate the supercharger gears from the engine vibrations is a noise isolating coupling, located as shown above on the new Eaton Twin Vortices Series TVS® supercharger. A crucial component in this coupling is its Single Spring Isolator (SSI) which is situated between an inner and outer hub which enclose the spring in an internal cavity. Each hub is pressed onto its own mating shaft, with the input shaft connected to the front hub and with the rear hub pressed onto the shaft that drives the gears which compress and drive boosted air into the engine.

The mechanical characteristics of the spring are selected to match specific engine vibration characteristics, with a goal to reduce or eliminate the transmission of certain vibration frequencies to the supercharger gears from the engine. The inner and outer hubs form a free pocket, i.e. the spring under no load will actually float in the cavity formed by the hubs. The spring can travel in both directions: the spring "winds up" by tightening onto the inner hub; alternately, the spring can also "wind-out", in which case the spring grows larger and eventually contacts and becomes constrained by the outer hub. The total travel is limited by the radial clearances between the inner and outer hubs: if the clearances are too large the spring may wind-up or wind-out excessively, resulting in high stresses and decreased fatigue life. Thus, the specific design and related tolerances are crucial to optimize noise isolation and spring fatigue life.



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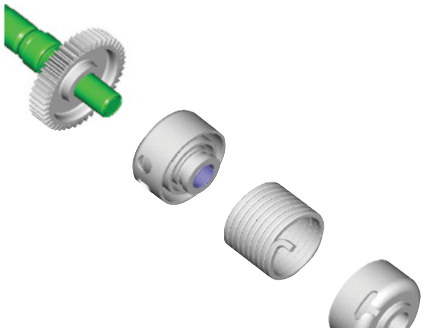
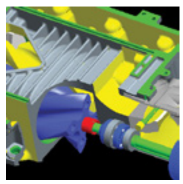
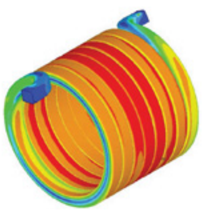
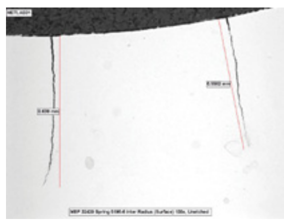


Strain response and duty cycle

To assess the structural response of the spring under "wind-up" and "wind-out" conditions, an FE model was developed which captured three dimensional strain conditions at over 170,000 points in the spring. Geometric nonlinearities, i.e. sliding contact with friction, were captured by the FE model whilst material nonlinearities were taken into account by fe-safe. The FE model allowed Eaton to develop a response model that determined strain as a function of shaft torque. Next it was necessary to develop a composite set of (torque) loading scenarios (sometimes referred to as a duty cycle) for the spring, considering about a dozen different engine loading scenarios, e.g. strong acceleration from a standing start, gear change, pulling a trailer up a long hill, deceleration, etc.

Intelligent load processing

For most of the load cycles, the "as-measured" torque signature contained more than 300,000 points. To reduce analysis time, fe-safe includes a signal processing algorithm (peak-valley gating) which extracts a set of load points that achieve a near equivalent fatigue damage with only a fraction of the original load points (for example 90% of the fatigue damage can often be captured by considering less than 10% of the load points).

Fatigue and material modeling

The next step was to determine which fatigue model was appropriate for the situation and the materials being considered. The spring was the main concern, and since it was made from a common high-strength steel, proven fatigue-related material properties were readily available.

In correlating fe-safe results with test, Eaton was able to capture some cracks in the spring during abuse testing. This also helped confirm which algorithm to use: the principal strain criteria, with Morrow's mean stress- correction.

The "Coffin-Manson-Basquin" relationship between local strain amplitude and endurance was selected in fe-safe and a number of different relevant settings were selected, e.g. Neuber correction for local plasticity, mean-stress correction on critical plane analysis, shot peened surface finish, etc. The fatigue life analysis also needed to consider multiaxial stress components (i.e. bending together with torsion).

Important insights

Eaton realized a number of important design and reliability insights by combining its traditional FE stress analysis tool with the modern fatigue analysis methods available in fe-safe. Some of these insights included:

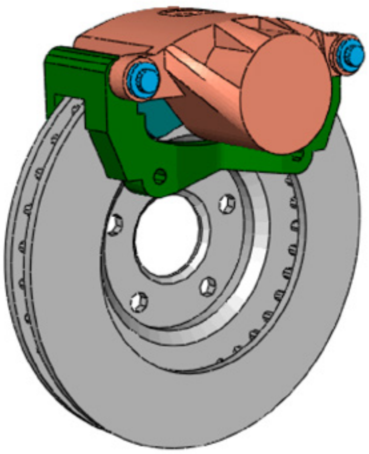
- The point of highest stress from the FE model was rarely the location of minimum fatigue life (crack initiation)
- The integrated FE and fe-safe analysis quickly revealed how changes in friction produced surprising and non-intuitive changes in loads and fatigue life
- Using fe-safe enabled the development of a robust design process; variations (within tolerance) in as-manufactured design geometry can now quickly be assessed to determine the effects of tolerance on fatigue life.

About Eaton

For nearly a century, Eaton has been supplying the global automotive industry with highly engineered products that help to increase fuel economy as well as improve a vehicle's overall efficiency, performance and control. In addition to serving global OEMs, Eaton is also a leading manufacturer of products available in the automotive aftermarket through a network of qualified distributors and retailers. Eaton's automotive business employs nearly 10,000 people and is headquartered in Southfield, Michigan, USA. It has Engineering, Research and Development centers in Marshall, Michigan; Turin, Italy; Baden Baden, Germany; Pune, India; Shanghai, China; and Prague, Czech Republic and more than 30 manufacturing locations worldwide. Eaton supplies nearly every automotive, vehicle and engine manufacturer in the world with high-quality parts, systems and services on a daily basis. To learn more, please visit our website www.eaton.com, please call +1 269 781 0469, or please email: infosupercharger@eaton.com.

Source: SIMULIA Community News

High Fidelity Anti-Lock Brake System Simulation Using Abaqus and Dymola



Summary

Accurate simulation of an anti-lock brake system (ABS) requires detailed modeling of separate subsystems in different physical domains. Creating refined models of the brake, wheel, and control components with a single analysis tool is difficult, if not impossible. The strategy of co-simulation can be adopted to meet this challenge; different simulation tools can be used simultaneously to create multi-disciplinary and multi-domain coupling.

In this Technology Brief, a co-simulation approach using Abaqus and Dymola is used to achieve a realistic system-level simulation of an ABS. The tire, wheel, brake caliper mechanism, and road are simulated with a detailed Abaqus finite element model while the brake system control algorithm and hydraulics and are simulated with Dymola.

Background

An anti-lock brake system can be viewed as an assembly of mechanical and logical subsystems. The mechanical system consists of the tire, wheel, disc, and brake caliper hardware, while the logical system consists of the hydraulics and control electronics.

Abaqus, with its strong nonlinear continuum capabilities and versatile modeling features, has proven to be a valuable tool for tire simulations. Dymola, with its ability to efficiently model logical abstractions, is an ideal candidate for the simulation of the hydraulic and control systems.

Neither tool in isolation is an ideal choice for conducting a high-fidelity system-level simulation of the entire ABS. To this end, a co-simulation approach is demonstrated in which Abaqus and Dymola are coupled at run-time to simulate the dynamics of the system in a way that cannot be achieved with either software acting alone. The structural response of the wheel system and the logical response of the control system are exchanged between Abaqus and Dymola in a synchronized manner. The braking loads thus applied to the wheel are controlled by the ABS electronics logic based on input from the mechanical system.

Analysis approach

For this study, a single wheel with no suspension components is considered. To enable co-simulation, the Abaqus and Dymola models must have a communication interface. This is achieved by defining sensors and actuators in the Abaqus model that deliver and receive signals to and from the Dymola logical model. The braking analysis consists of slowing the wheel assembly from an initial velocity of 10 m/s with a ramped brake pedal force.

The mechanical state of the brake system is used as the controlling signal; it is used by Dymola to actuate the caliper in the Abaqus model such that braking forces are applied and modulated so that the wheel will not lock, or fully slip on the road. This workflow is discussed in detail in the following sections.

Brake control system model in Dymola

The block diagram of the Dymola logical model is shown in Figure 1. The braking system consists of a single brake caliper cylinder connected to a master cylinder via a three port valve. The three port valve has three modes of operation: a pressure increase mode in which the master cylinder is connected to the slave, a hold mode in which all ports are disconnected, and a pressure decrease mode in which the slave cylinder is connected to a tank. This system represents the simplest form of ABS implementation in which brake fluid is not returned to the master cylinder until the braking event has taken place.

Key Features and Benefits

- Abaqus and Dymola co-simulation allows for the coupled, time domain simulation of compliant structures embedded in complex, logically controlled systems
- Accurate, detailed static and dynamic non-linear tire modeling in Abaqus

Source: Technology Brief

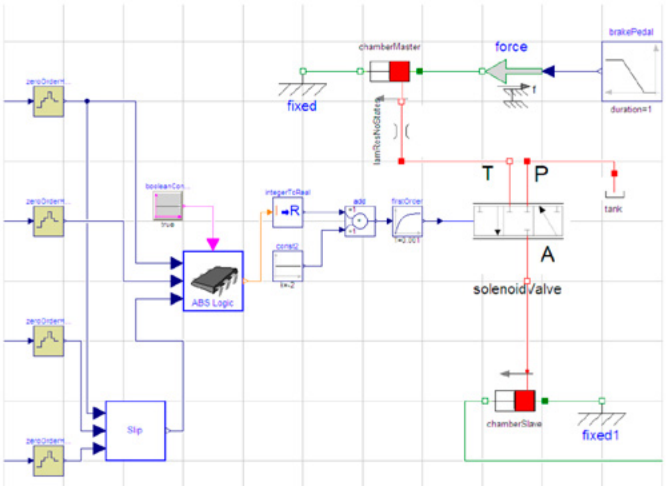


Figure 1: Block diagram of the brake system logic and hydraulics and control model in Dymola

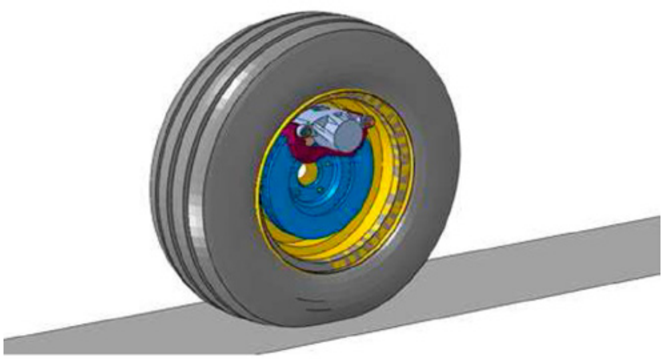


Figure 2: Abaqus tire, road and brake model

The control mechanism is simulated by making the operating state of the three port valve depend on wheel acceleration and slip. In the control algorithm [1], the required inputs are wheel angular velocity ω, angular acceleration ω, rolling radius r and hub longitudinal velocity V_x. The input signals to the controller are sampled with a period of T_s = 1 ms. The longitudinal slip is calculated as

The ABS is triggered when the wheel deceleration falls below the prescribed threshold -a. At that moment, pressure is held constant until the slip exceeds a threshold λ_T, at which point pressure is dropped to a certain value.

Pressure is then held again until a positive acceleration A is reached. Now the pressure is increased until the acceleration drops to ***a***. At this stage pressure is increased slowly via alternate hold and increase commands. This process allows the peak portion of the friction characteristic curve to be traversed slowly before the unstable side of the curve is reached. The cycle begins again once the –a acceleration threshold is crossed.

Aside from this regular control cycle, the controller is deactivated when the longitudinal velocity is under a certain level. In addition, a timeout parameter is used to reset the ABS control algorithm if it remains in one state for an extended period of time. This is necessary to prevent the controller to be locked when brake action is no longer required.

This is a rule-based algorithm, which is popular in production systems. An alternative is to use a model-based algorithm, an example of which can be found in [2].

Tire, road and brake model in Abaqus

The Abaqus model, shown in Figure 2, includes the tire, wheel, brake caliper and rotor subassembly, and the road. The tire is first pressurized and placed in contact with the road under the vehicle weight acting on the wheel. A steady state transport analysis is then performed in Abaqus/Standard to compute the state of stress and deformation in the tire corresponding to a given forward velocity with no braking. Optionally, a cornering radius can be specified as well.

The tire in its free-rolling condition is then imported into Abaqus/Explicit for the braking co-simulation with Dymola. As Abaqus/Explicit computes the state of stress and deformation in the rolling tire, the wheel angular velocity and acceleration are communicated at frequent intervals to Dymola via the Abaqus sensors. The required braking pressure is computed by Dymola and communicated back to Abaqus/Explicit to be applied to the brake caliper cylinder. The brake pads are pressed against the brake rotor to produce a braking torque that decelerates the wheel assembly.

Co-simulation scheme

The following non-iterative co-simulation scheme is used:

At each time increment of the Abaqus simulation, sensor information is computed and communicated to Dymola via a socket-based interface.

Dymola reads the Abaqus sensor information as inputs to the control logic and integrates in time with an increment size equal to that used by Abaqus/Explicit. The actuating signal computed in Dymola is communicated back to Abaqus, which applies this newly computed load in the next increment.

The process is repeated until the simulation time is completed.

Co-simulation results

Figure 3 shows the hub longitudinal and circumferential velocities during the co-simulation. A difference between the two quantities represents a slipping condition. The slip is initially large, but the controller is able to prevent wheel lock.

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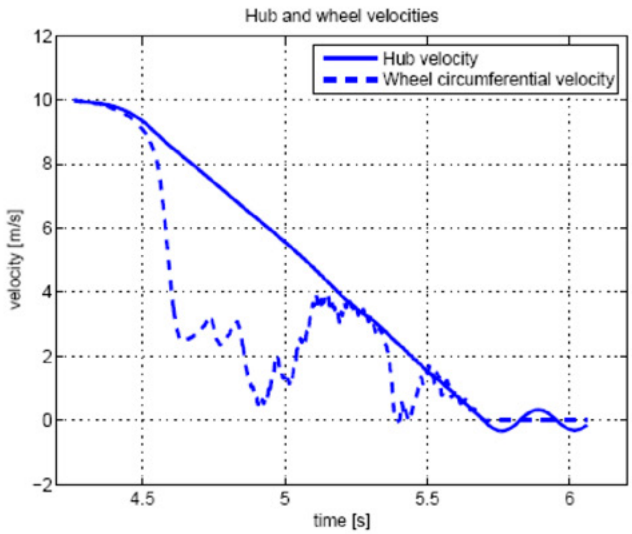

Figure 3: Hub longitudinal and wheel circumferential velocities during co-simulation

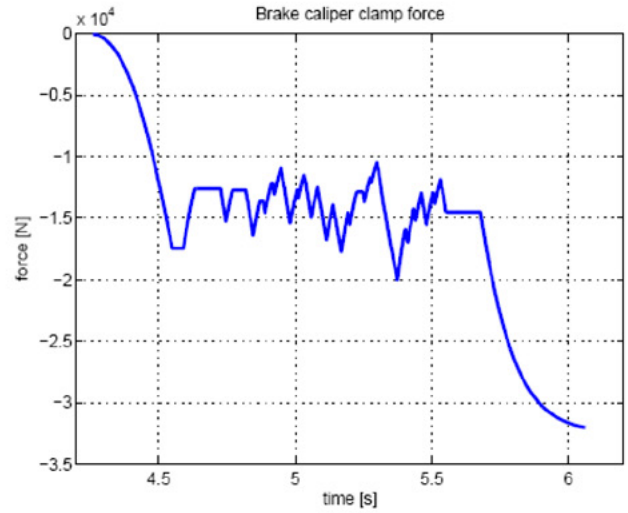

Figure 4: Brake caliper clamping force during co-simulation

Figure 4 shows the brake caliper clamping force during the co-simulation. The rapid force build-up and release phases are clearly visible.

Conclusion

In this Technology Brief, a co-simulation scheme for analyzing an anti-lock braking control system is developed. A high-fidelity tire model in Abaqus is combined with a hydraulic braking control system model in Dymola, highlighting how different simulation packages can be integrated to perform realistic system-level simulations. The existing advanced tire modeling capabilities in Abaqus can thus be applied to a larger class of real-world operating conditions. The co-simulation approach can be extended to full vehicle models under varying road conditions, hydroplaning analyses, and optimization.

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Abaqus References

For additional information on the Abaqus capabilities referred to in this brief, please see the following Abaqus Version 6.13 documentation references:

- "Amplitude curves," Section 34.1.2 of the Analysis User's Guide
- "VUAMP," Section 1.2.7 of the User Subroutines Reference Guide
- User's and Installation Guides for Logical-Physical modeling using Abaqus and Dymola, DS Knowledge Base article QA00000008585
- Abaqus/CAE Plug-in for Logical-Physical modeling with Dymola, DS Knowledge Base article QA00000008584

Source: Technology Brief

Simulation of Airbag Deployment Using the Coupled Eulerian-Lagrangian Method in Abaqus/Explicit

Acknowledgements

Dassault Systèmes Simulia Corporation would like to thank the BMW Group for providing the experimental results and the finite element models used in this study.

Summary

The uniform pressure method (UPM) approach to simulating airbag deployment has been widely used in the automobile safety industry. The defining assumption of UPM, specifically that pressure in the airbag is spatially uniform during inflation, makes the approach most applicable for 'in-position' (IP) analyses with fully inflated airbags. In contrast, an analysis may be characterized as 'out-of-position' (OoP) if the occupant interacts with the airbag before it is fully deployed. Prior to complete inflation, large spatial pressure gradients can exist in the airbag, violating the assumptions of the UPM approach.

The advancement of airbag regulations and technology necessitates the consideration of OoP scenarios. An accurate analysis thus requires a tool capable of simulating the flow of gas during the inflation process.

Abaqus/Explicit offers a sophisticated Coupled Eulerian-Lagrangian (CEL) technique that can be used to simulate dynamic gas flow in the airbag. The flow-based CEL method offers a more realistic prediction of airbag shape and pressure distribution during all stages of deployment.

Background

In the UPM approach to airbag inflation simulation, pressure can vary temporally, but at any instant the spatial distribution of pressure is uniform. The validity of the assumption is greatest at full inflation; therefore UPM is traditionally used for simulating IP load cases where the occupant impacts a completely inflated airbag.

In a static OoP safety test, the engagement of the occupant with the airbag starts when the airbag is only partially

Key Features and Benefits

- The Abaqus/Explicit Coupled Eulerian Lagrangian (CEL) technique provides the ability to model gas flow in the airbag and include the effects of surrounding air during deployment
- Ability to easily enforce contact interactions between the Lagrangian bodies and the materials in the Eulerian mesh using the powerful and robust general contact algorithm
- Extensive material library to model woven airbag fabrics and gas equations of state

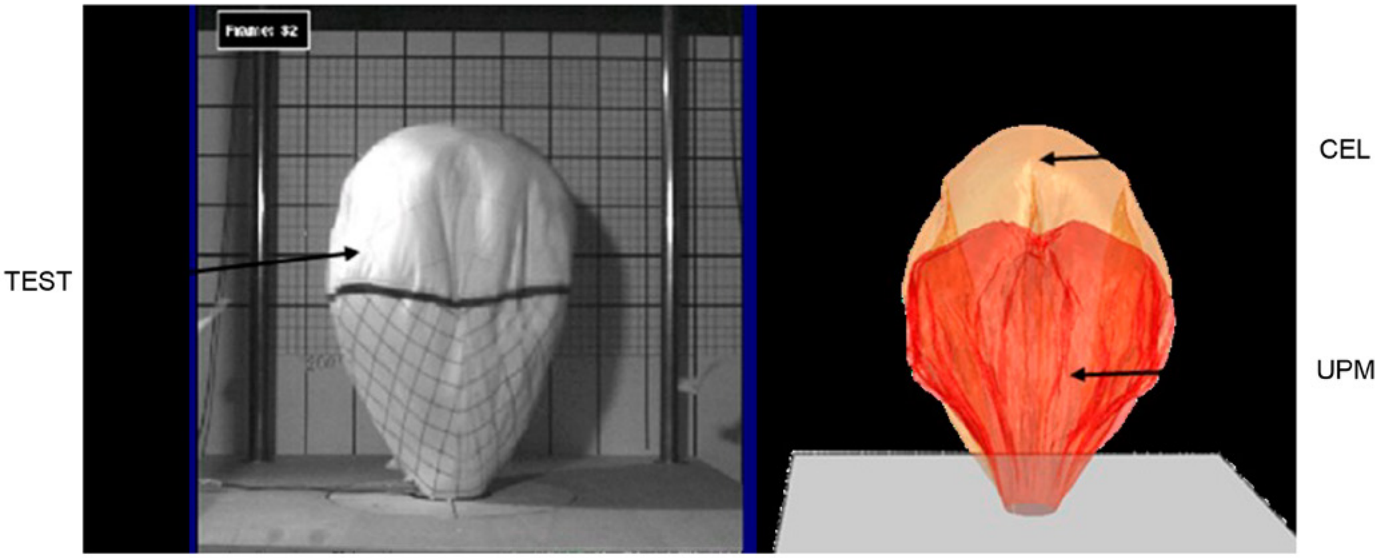

Figure 1: A folded airbag deployment at 16 ms: Test, CEL & UPM simulation approaches

Source: Technology Brief

deployed. During the initial stages of inflation, large spatial pressure gradients exist inside the airbag; some regions of a tightly folded bag will not "see" the inflator gas before the bag unfolds. The UPM assumption thus breaks down, and the motion of the gas in the airbag must be considered for such cases. The Coupled Eulerian-Lagrangian (CEL) technique provides a higher fidelity approach by simulating the gas flow inside the airbag. Consequently, this method predicts a more realistic deployment and computes the spatial and temporal pressure history inside the airbag accurately, even during the early stages of inflation. Figure 1 compares the predicted shape of an initially folded airbag at 16 ms using the two approaches.

Working Group Airbag

In the late 1990s, German automobile manufacturers formed a 'working group' to evaluate and develop a common methodology for out-of-position simulations [1]. The working group used a standard 60-liter driver airbag model for evaluating different simulation techniques. Two versions of the driver airbag, flat and folded, were used for the evaluations. The same two working group airbags are used for the present demonstration of the CEL method in Abaqus/Explicit.

The test configuration consists of a freely suspended hemispherical headform which is in initial contact with the airbag (Figure 2). During deployment, the airbag pushes the headform, and the acceleration is measured and correlated against the test data.

Finite Element Analysis Approach

The Lagrangian airbag is discretized with membrane elements. The fabric constitutive model is anisotropic and nonlinear, and captures the independent loading and unloading mechanical response of a woven material in each of the three component directions: fill, warp, and shear.

In a traditional Lagrangian analysis nodes are fixed within the material, and the elements deform as the material deforms. Lagrangian elements are always 100% full of material, so the material boundary coincides with an element boundary. By contrast, in an Eulerian analysis nodes are fixed in space, and material flows through elements that do not deform. Eulerian elements may not always be completely full of material; many may be partially or completely void. The Eulerian mesh for these simulations is a simple grid constructed to extend well beyond the Eulerian material boundaries, giving the material space in which to move and deform.

The airbag inflator is represented by a number of nodes at locations that approximate the inflow points. A vector is specified at each of the inflator nodes to represent the direction of the gas inflow. The velocities at the nodes of the inflator elements are obtained by solving the momentum equations based on the input mass flow rate, area, and the direction vector. The temperature and the mass flow rate of the gas entering the airbag is specified at the inflator nodes as a function of inflation time. In the experiment, the inflator gas composition changes with time, but in the simulation the inflator gas composition is assumed to be constant.

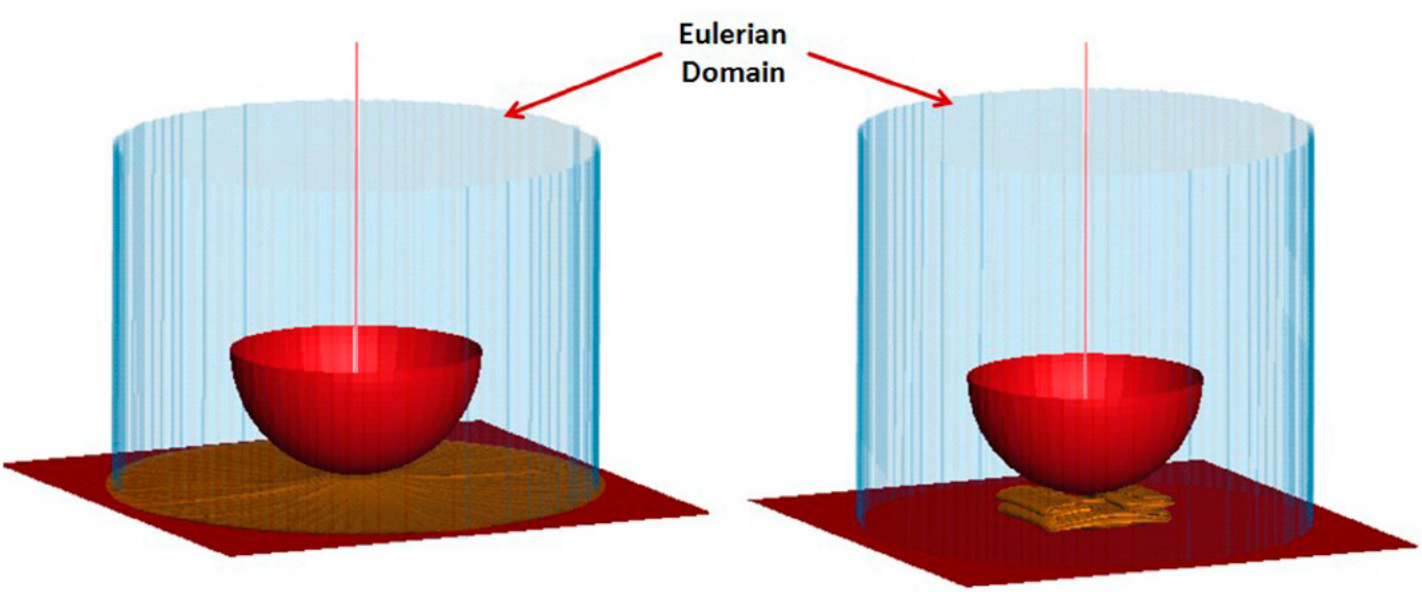

Figure 2: Initial configurations of flat (left) and folded (right) airbag simulation models

Source: Technology Brief

An Eulerian element can contain multiple materials at the same time. The Eulerian volume fraction (EVF) is computed for each material at every time increment, and based on the EVF, the material surfaces for every element are determined. These Eulerian material surfaces can interact with Lagrangian surfaces, such as the airbag. The Eulerian domain is initially filled with air. When the inflator fires, the gas fills the airbag and pushes the air out. Abaqus/Explicit general contact captures both the Lagrangian contact and the Eulerian-Lagrangian contact. The latter is defined only between the inflator gas and the airbag. No contact is defined between the outside air and the airbag. It is safe to assume that the air cannot re-enter the airbag due to the high inflation pressure.

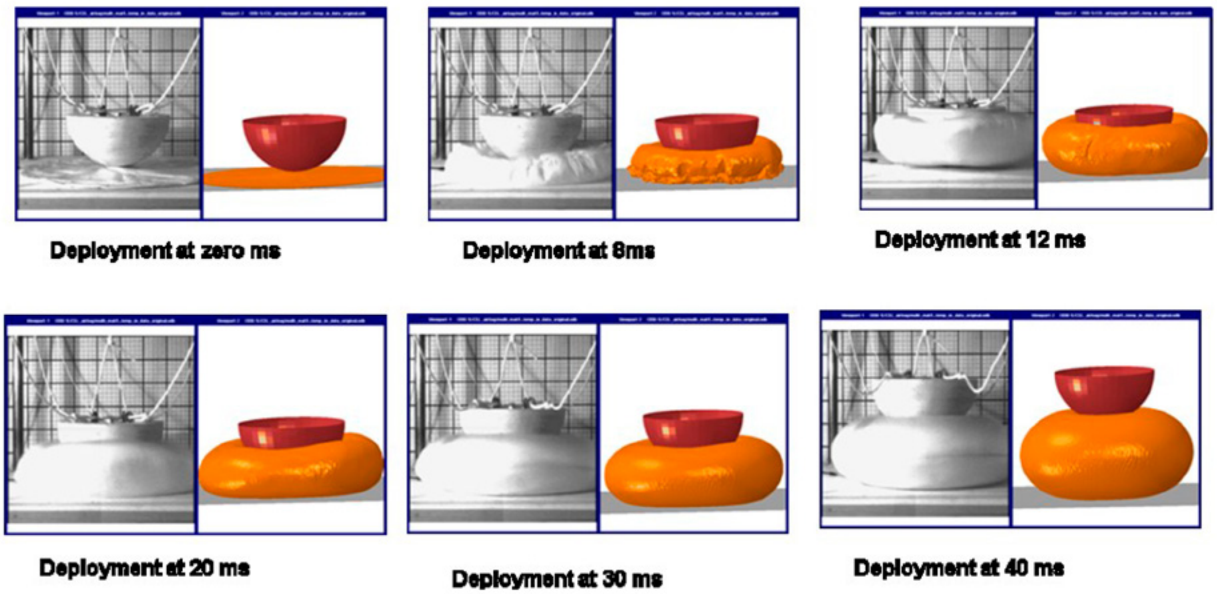

Figure 3: Flat airbag deployment, experimental results and CEL prediction

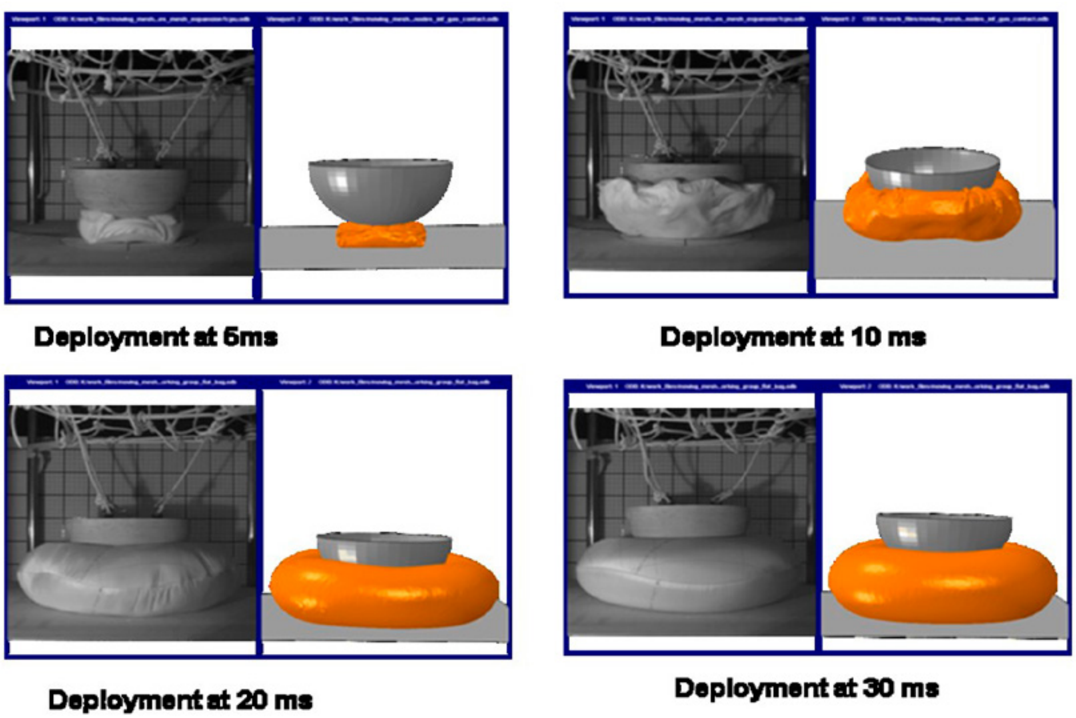

Figure 4: Folded airbag deployment, experimental results and CEL prediction

Source: Technology Brief

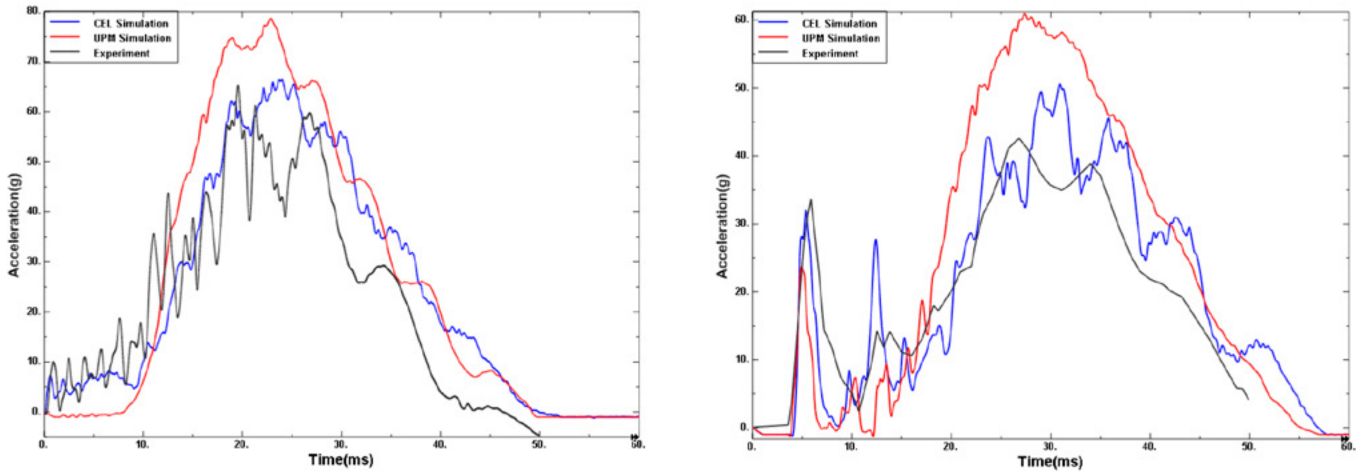

Figure 5: Headform acceleration for the flat (left) and the folded (right) airbags

Results and Conclusions

A 5 mm uniform Eulerian mesh is used for both models. Figures 3 & 4 display the comparison of the working group flat and folded airbag experimental deployment with the CEL predictions. Figure 5 shows the comparison of the headform acceleration for the flat and the folded airbag simulations respectively. For both airbag models, the acceleration history as well as the airbag deployment correlates reasonably well with the experiment.

It is clear from Figure 5 that the UPM approach does not capture the acceleration history well during the initial stages of deployment. The initial peak as well as the maximum peak acceleration is more accurately captured in the CEL simulations. In both the airbag models, the CEL simulation better captures the oscillations in acceleration plots.

The above correlation between the experiment and the CEL method demonstrates that Abaqus/Explicit is capable of predicting realistic results even in the early stages of the airbag deployment; hence, this method can be successfully used for the out-of-position load cases.

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- Abaqus Analysis User's Guide:

  'Eulerian Analysis,' Section 14.1.1

  'Eulerian Elements,' Section 32.14.1

  'Eulerian surface definition,' Section 2.3.5

  'Defining general contact interactions,' Section 36.4.1

Source: Technology Brief

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