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Aerodynamic Optimization: Automotive Engineering's Next Strategic Frontier

By Bruce Jenkins, Principal Analyst, Ora Research

With the unprecedented demands on today's vehicle engineering organizations, auto makers face a daunting challenge to reach their next targets for aerodynamics drag using traditional tools and methods. Trial-and-error development using wind tunnel testing achieved a coefficient of drag of 0.3. Introducing digital simulation to sequentially improve designs brought C_D down to 0.24 for today's best performing cars. But most companies have the next target set to 0.2. Without either a radical increase in time and resources—not a realistic solution for most—or else a radically more efficient and effective approach to aerodynamics engineering, this target will remain all but out of reach.

The pressures constraining engineering organizations' efforts to achieve these targets are greater than ever. Model proliferation, a competitive necessity, is staggering—the passenger vehicle industry has seen a 40% increase in the number of models produced in the last 15 years, by the same number of OEMs. Design aesthetics are a challenge—customers demand aesthetically pleasing products and numerous model options, yet engineering departments have not been allowed to grow to meet these demands. Costs to incrementally improve performance are increasing as even small gains become harder to achieve.

Meanwhile the march of increasingly stringent regulatory requirements continues, while evolving test procedures involving real-world conditions make goals harder to reach. The target for CO_2 emissions is a 30% decrease over the next 10 years, an average reduction of 2g/km per year. Fuel economy has increased by 30% in the last five years, but will need to increase another 100% in the next 10 years to meet regulatory standards.

To achieve these interlocking and often competing goals, auto makers will have to find ways to evaluate 10 times the number of designs in half the time as before. Will they do more of the same—more manpower, more prototypes, more performance compromises? Or will they instead adopt a solution that more and more leading-edge engineering organizations are discovering—a new scientific process that systematically explores all combinations of design change possibilities to efficiently understand their potential and interactions, then optimizes a chosen design to arrive at the best possible solution?

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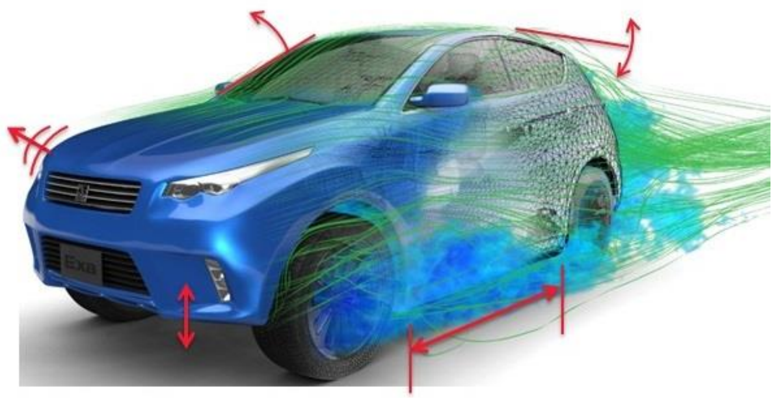
Crucial to hitting performance targets: Design exploration and optimization



Many of these design challenges—aerodynamics, thermal management, noise, cabin comfort and more—are heavily influenced by the complex fluid flows over and through the vehicle. The challenge faced by vehicle manufacturers in each design stage is the urgent need for information about how to improve the design. Because of its inherent advantages over physical prototype testing methods, digital simulation can bring much more feedback about the design performance into each stage of development, improving the ability for designers and engineers to innovate in balancing design aesthetics with aerodynamics.

Historically the most common method of applying simulation, especially in cases involving complex flow physics or geometrical changes that are not well understood, has been to guess which combination of parameter changes will be optimal. Essentially a method based on engineers' intuition about the most likely solution to a problem, such an approach begins by performing one or more simulations on baseline geometry. From the results, engineers reason about the behavior of the fluid system and thus about likely performance changes possible by changing aspects of the baseline geometry. The extent to where and how the geometry can be changed is provided by the design department. The engineer guesses based on intuition and previous experience which design parameter combinations are to be tested. This is really the only option he has. For example, if five design parameters each with five possible variants are to be evaluated, 5 to the power of 5 or 3125 combinations would need to be evaluated. There are, in practice, not enough computational resources or time available for such an activity. The problem becomes even more intractable with the increasing number of parameters and their variants. The tests provide hit-and-miss results, where the frequent misses require coming up with new guesses.

This approach relies on the seasoned experience of the engineer, and is limited to changing a few things at a time. Even then, if changes are too large or too many changes are made at once, the assumptions of impact on flow results are no longer valid, and the improvement is not achieved.

Fortunately for engineering organizations, help is at hand. A fast-emerging solution to the inefficiencies of the guessing approach is design space exploration and design optimization—terms that describe both a class of quantitative methods and a category of software tools that let engineers systematically and automatically explore very large numbers of design alternatives, and identify those with the most optimal performance parameters. For aerodynamics engineers, a leading implementation of this capability is Exa Corporation's PowerFLOW Optimization Solution, which combines statistical analysis with the ability to simulate some of the

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world's most complex fluid flow problems. Unlike the old intuition-based approach, this new approach can be used even by new engineers, and can also handle many more changes in parallel.

How the technology works

Exa's PowerFLOW Optimization Solution is a fully automated optimization process that uses statistical analysis methods to systematically explore the potential of design alternatives based on results from PowerFLOW simulations. A baseline geometry is combined with a design space of shape changes to create a series of models, then the simulation results are used to create a response surface to answer various design questions. Plug-in integrations with the market-leading optimization analysis tools ESTECO modeFRONTIER and SIMULIA Isight enable easy setup and automated execution. The PowerFLOW Optimization Solution explores large numbers of design alternatives and generates a mathematical "response surface" from a small number of simulations. Advanced algorithms then identify trends and evaluate trade-offs, providing a multidimensional analysis beyond the capability of human reasoning. Exa's high-performance visual flow analysis tools are then used to understand and explain trends seen in the statistical analysis. Notable is that, from a work process standpoint, this approach fits perfectly with how an automotive design studio works with the company's aerodynamics department: Designers provide areas that aerodynamicists can work on, then the aerodynamicists can parametrize the design space in order to search for better design solutions within the constraints provided by the designers.

What's unique about Exa's approach?

The strength of Exa's solution is grounded in the accuracy of its PowerFLOW simulations which correctly predict real-world flow conditions without compromising geometric detail, its high-performance visualization tools connecting flow results to statistical analysis, and its design-quality morphing which ensures results are acceptable from a design perspective. Key to the solution is the new PowerFLOW Integration Node, which allows easy workflow setup and execution within either modeFRONTIER or Isight. Also critical is the ability to connect statistics to flow results with Exa's PowerINSIGHT for automated simulation results generation, analysis and reporting, and its PowerVIZ for 3D visualization and analysis of simulation results.

In addition PowerDELTA, Exa's tool for creating and updating simulation models, has been enhanced to automate rapid creation of design alternatives for design space exploration; using PowerDELTA's design space variable table, the user identifies design space variables upon model creation in PowerDELTA. PowerCASE, Exa's tool for setup of CFD cases, provides an intuitive, fast interface for preparing cases with any level of geometric complexity; as with PowerDELTA variables, the user can identify design space variables upon creation in PowerCASE for use throughout the CASE file.

Working in the real world: Project successes

Using its PowerFLOW Optimization Solution, Exa has completed over 100 design optimization projects for aerodynamics, thermal packaging, aeroacoustics and brake cooling, showing performance improvements totaling up to 13%—far beyond what would have been possible with improvement efforts based on guessing

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which design parameter combination is optimal. Many of these projects included multi-attribute and cross-discipline studies, balancing competing performance targets to satisfy multiple objectives; Exa's automated optimization process was able to identify solutions that were non-intuitive and thus unlikely to have been discovered. Further, these achievements often came *after* sequential design efforts had been carried out.

In aerodynamics, over 60 production projects have been carried out, yielding improvements of 1% to 6% in fuel economy, with multi-objective optimization used to balance tradeoffs between fuel economy and handling. In acoustics, over 10 projects have been done, achieving 0.5dB to 2dB reductions in noise—up to 2dB with late-stage design, and up to 5dB with early-stage design. In brake cooling/component optimization, over 10 production projects have resulted in 5% to 10% performance improvements including reduction in aerodynamic forces and reduction in brake cooling time, using multi-objective optimization. In thermal packaging, over 30 projects—early projects for predicting package potential, plus later projects that added operating conditions/aerodynamic impact—achieved up to 12% increase in mass flow rate and up to 4-degree reduction in top tank temperature. Multi-attribute/cross-discipline projects involving cooling drag achieved up to 5% improvement in fuel economy, up to 10% increase in mass flow rate, and 3-degree reduction in top tank temperature.

Case study: Early-stage aerodynamic optimization of an SUV

In a project by a leading auto maker to develop a new sport utility vehicle, a key goal was to achieve a state-of-the-art drag level. To meet this aggressive target, feedback from aerodynamics had to be included in early-stage design. As the first step in the process, a detailed simulation model was built. The styling surface was combined with engine-room and underbody detailed geometry from a similar-size existing vehicle. From a detailed analysis of the flow field, potential areas for improvement were identified. The aerodynamics team worked with the styling team to determine the range of design changes that would define the design space. A total of five parameters, each representing a design change to the upper-body shape in a certain range, were defined to form the design space.

In the second step, Exa's PowerFLOW Optimization Solution was brought into play. A variant of its response surface method (RSM) involving both design of experiments (DoE) and adaptive sampling techniques was applied to characterize the effects of the design changes. The selection of an adaptive approach was made given the number of parameters was greater than five, and the timeline for the project allowed for an iterative approach. If the project were to consist of fewer parameters, an RSM approach with only a single DoE would have been used. In general, any project involving more than two simulations should become a DoE to reap the many benefits of Exa's PowerFLOW Optimization Solution.

This characterization was followed by an optimization step to find the best possible drag improvement from these design changes. The optimum design calculated by the response surface was then validated by CFD simulation. At the same time, wind tunnel tests of a fully detailed clay model of the vehicle confirmed the performance improvement predicted by the simulation results.

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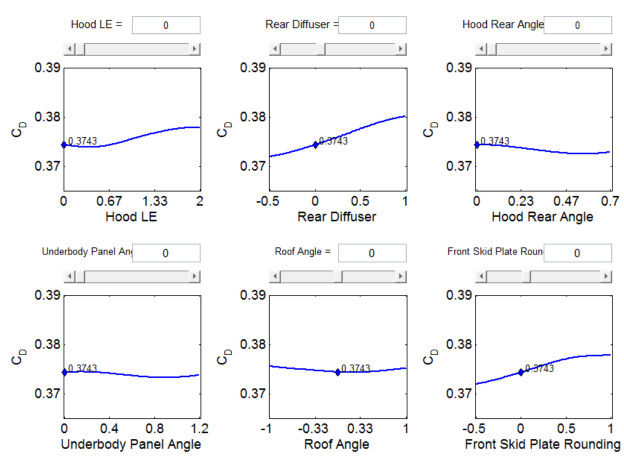
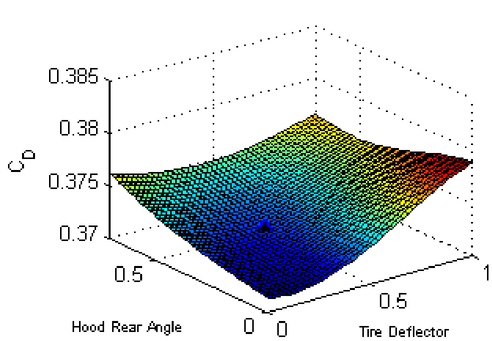
Critical to success of this project was how response surface models function as a representative or surrogate of the true response of CFD simulations. They allow interrogation methods such as analysis of trends, the main and interaction effects of parameters, and global search of optima to be performed at little or no cost once the model is built. Also, multiple response models can be built from the same input data, providing an analytical way to relate multiple objectives. This additional information extracted from the data set via the response surface model gives each individual simulation more and lasting value to the design refinement process.

Response surface methods let engineers focus on creating parameters that will have significant impact on performance while maintaining the design character of the vehicle. The software then performs the challenging tasks of finding complex trends, interactions and optima.

Response surface models take as input data from simulations in the form of independent and dependent variables. The independent variables are the design space (DS) parameters, while the dependent variables are the response space (RS) parameters. As an example, a design space could consist of geometric morphs of a car's front fascia, rear spoiler and rear diffuser. An example of a response space could then be the car's drag coefficient, as well as front and rear lift coefficients. The response surface model constructs a mathematical representation of a response given the matrix of design space parameters and a vector of responses for a series of simulations.

Once the response surface model is constructed, a variety of analysis techniques can be used to extract information from the data set. The first level of analysis is simply visualization of the response surface itself. This can be done by viewing the trends in one parameter direction at a time so the response surface appears as a line or in two parameter directions such that the response is a visible surface. When the response surface model has many dimensions, the one parameter or 1D visualization, shown at right, is useful to simultaneously view trends in many dimensions from a single location in the design space.





The two-parameter or 2D visualizations, shown at left, help predict interaction effects between parameters at a single location in the design space. More complex analysis of the response surface can be done by averaging parameter main effects over the entire design space to return which parameters have the largest effect on the response.

Finally, the response surface can be directly searched to find the predicted optimum configuration, or in the case of multiple responses, to create a predicted Pareto front, shown

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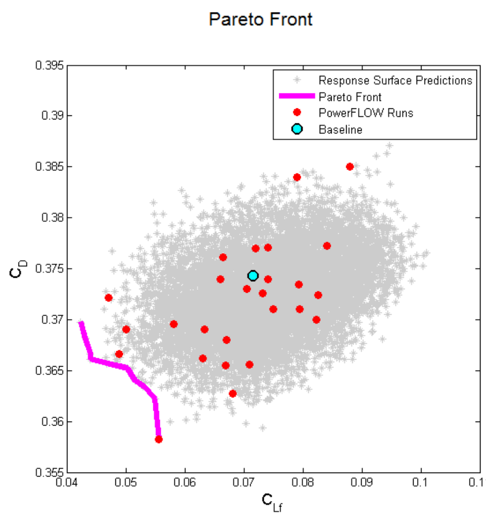
at right, in which the multiple response of the drag coefficient C_D and the front lift coefficient C_{Lf} are plotted. In optimization problems with more than one objective, the objectives often conflict with one another, so tradeoffs must be made among them. In this case, there will be one design with the best drag coefficient, another design with the best front lift coefficient, and an infinite number of designs that are some compromise of the two. The set of tradeoff designs that cannot be improved on according to one criterion without harming another criterion is called the Pareto set, and the curve plotting drag against front lift of the best designs is termed the Pareto frontier. This search can also involve restricting the design space to let the designer explore "what-if" scenarios.



Benefits and payback

By combining PowerFLOW accuracy with statistical methods for design, Exa's PowerFLOW Optimization Solution lets engineers accurately predict real-world flow conditions without compromising geometric detail. The solution delivers accurate predictions of multiple attributes across disciplines. Resulting trends and statistics are more accurate and lead to a better design. Advanced morphing techniques allow for design-quality solutions from statistical methods.

Project setup time is reduced by having fully integrated, easy-to-use setup tools and simulation workflow configuration. Fully integrated plug-ins to modeFRONTIER and Isight offer a simple interface for setup and execution. Easy-to-use Design and Response Variable tables in PowerDELTA, PowerCASE and PowerINSIGHT let the user define the optimization project while setting up the baseline simulation.

Project execution time is reduced and costly human errors are eliminated, as fully automated simulation process execution enables automatic execution of workflow for each simulation, automatic geometry modification and simulation case setup, and automatic simulation results collection.

The solution ensures that results are acceptable to design with studio-quality surface modification. Designers provide areas that aerodynamicists can work on, then the aerodynamicists can parametrize the design space in order to search for better design solutions within the constraints provided by the designers. Users can infinitely vary surfaces with Exa's patented, parametric, lattice morphing technique.

Multi-objective, cross-discipline optimization allows engineering departments to collaborate. For example, cooling packages can be optimized for both cooling performance and cooling drag impact. Engineers can simultaneously achieve improvements in fuel economy and top tank temperature. Project successes show up to 5% improvement in fuel economy along with 10% increase in mass flow rate.

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Exa's proven, documented optimization methodology and best practices offer engineering organizations confidence in project success. Methodology and best practices for study strategy using modeFRONTIER and Isight built-in run schedulers and process components are complemented by best-practice analysis techniques.

Conclusion

The aesthetic, performance, regulatory and resource challenges straining the capabilities of today's automotive engineering organizations find a uniquely powerful answer in Exa's PowerFLOW Optimization Solution. By combining statistical analysis with the ability to simulate some of the world's most complex fluid flow problems, this new solution enables engineers to evaluate many more design alternatives in much less time than before. Replacing guesses about which combination of parameter changes will be optimal with systematic, rational, rapid design exploration and optimization, the PowerFLOW Optimization Solution gives auto makers more complete, higher-fidelity visibility into product performance earlier in project schedules than was practical or even possible with previous tools and methods, dramatically strengthening their ability to compete and win in today's marketplace and beyond.

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