A New Testing Paradigm for Today's Product Development Process – Part 1

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Modern product development increasingly relies on simulation methods to optimize functional performances, moving away from the test-analyze-fix approach of physical prototypes to the computer-aided, engineering-based, virtual prototyping approach. Contrary to the belief that this would reduce the demands for testing, it has opened new applications, new challenges and opportunities. Test data play a critical role on each level of the development process – from product benchmarking, target setting, model verification, load analysis, hybrid model building to product qualification and performance monitoring. What is clear is that requirements for accuracy, test, ease of analysis and execution speed are more stringent than ever before. As a result, the whole paradigm of mechanical testing must be reconsidered in view of this new role as an essential enabler in the optimization process of virtual prototyping. Advancements in simulation go hand in hand with advancements in testing, and only their combined use will be able to push the design envelope to shorter and higher quality product development cycles.

The driving factors in modern product development are the competitively critical, but conflicting, demands to come up with more innovative designs and get them to the market before anyone else. This means making better products in a shorter time and at a lower cost. A major step was the shift towards a 'digital' design approach. Most companies have adopted an all-digital development environment for design (computer-aided design, or CAD), covering the "form-and-fit" stages of the process in a "virtual space." Similarly, numerically controlled machining, robots, and a direct link of manufacturing with CAD models allow a computer-aided manufacturing (CAM) process. Many companies also invest heavily in product data management (PDM) systems and explore collaborative business models.

But next to knowing how a product looks and how the components fit together, it is as important to get the design to perform as expected. For example, noise and vibration, reliability and safety are key performance factors, not only from a competitive point of view, but they are also increasingly imposed by legislation. To take these into account properly in the design is a complicated process, since they may depend on or even be in conflict with each other (e.g., in their relation to weight).

These performance factors were traditionally dealt with late in the development process using physical prototypes, where they appear as 'problems' rather than as true design targets. But at that late stage, many development 'gates' have been passed, and the main design decisions are frozen, leading to costly, suboptimal, 'palliative' solutions. The answer has been the recent evolution toward the use of numerical models for this part of the development process, leading to a virtual-prototype engineering concept based on simulation tools. Detailed structural-mechanical models allow simulating the performances and adapting the design to meet prior set targets. Examples are the many structural finite-element, vibro-acoustical, multibody, aero-acoustics, durability, thermal, etc., simulations that are performed for each design. This obviously leads to the question of what the role of testing will be in this 'digital' age.

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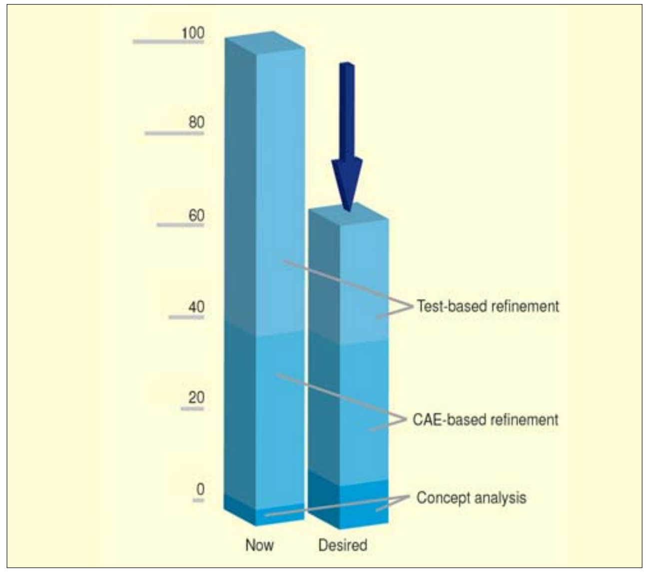

Figure 1. Process innovation targets.

Combining Test and Simulation

The objective (by necessity) is to achieve a breakthrough in the development process, leading to development cycles expressed in months instead of years. This can only happen if the engineering of critical product qualities is shifted much more to earlier development stages. This can be implemented by using upfront analysis at the concept stages, addressing refinement and cross-disciplinary product optimization using virtual models, and performing in-depth testing only on a reduced number of physical prototypes. This concept is expressed in Figure 1, indicating the relative effort spent (now and desired) in each stage of development.

While there is no doubt that a purely digital design is leading the way to the future, most engineers accept that a fully virtual design is still in the future. Insufficient calculation speed and performance of solvers is only part of the explanation, since important breakthroughs in terms of computing power, parallel processing, and optimized algorithms have been made. Missing knowledge on exact material parameters, lack of appropriate models for complex connections, or insufficiently accurate model formulations for some parameters remain major bottlenecks. The required optimization process is far too complex, covering too many (and interrelated) unknowns. Therefore, a combined use of test and simulation is adopted, making it possible to solve engineering problems faster and more accurately compared with exclusive use of one or the other.

The Y-axis in Figure 2 shows the required technical capability for some engineering task, such as system verification. The X-axis shows the time needed to complete the task. The 'Test only' curve shows how a task can be completed with traditional methods, typically based on testing and test data processing. The 'Simulation' curve shows how part of the task can be done faster, but typically not completed. As required technical capability is available, the traditional method can take over where simulation reaches limits, as shown with the 'Test' curve. Such a situation is typical for system verification, where test methods will be used to validate and calibrate simulation models – for example, extending the applicability of simulation models.

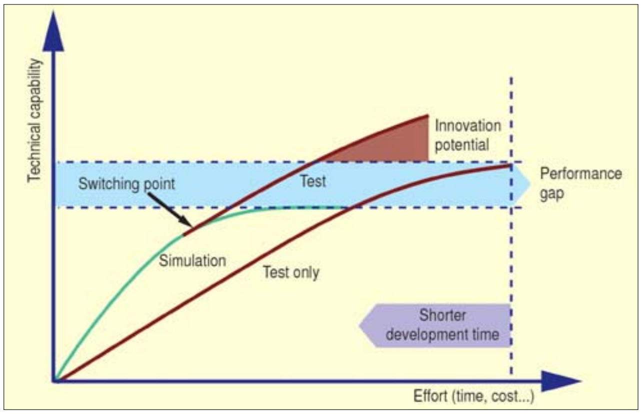

Figure 2. Combining test and simulation to deliver innovation

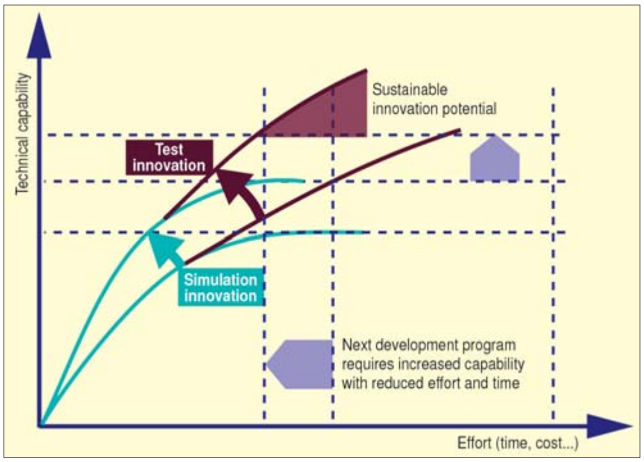

Figure 3. Sustainable innovation driven by innovation in test and simulation.

Figure 2 shows how a combination of test and simulation will not only deliver required technical capability, but also deliver more. This is essential, because in the next development program to which the engineering task will be applied, the required capability will increase as a result of constant product innovation. This is also illustrated in Figure 3. There is an interesting dynamic here. To meet the requirements for product engineering with more innovation embedded in the products and within shorter development cycles, progress is mandated in testing and simulation to always have the required technical capability for the next development program.

To adopt such an approach, the total development process has to be reconsidered in view of what is feasible at which stage. This requires trading off various attribute goals at the concept level before committing to detailed design and analysis. It also relies heavily on cascading system-level targets down to the subsystem and component level for concurrent design and engineering. At each level, multi-attribute optimization must be conducted. Also the effect of component and subsystem design changes on the total system performance must be evaluated. At each stage of the process, test data and test-obtained models contribute to increase the accuracy and even speed up the process. The appropriate use of experimental data and experimentally obtained models and their integration with numerical data, where available, in a true 'hybrid' simulation will no doubt prove to be the way forward. The discussed overall process is often referred to as the "Design V" (Figure 4).

While it is clear from the above overview that the role of testing for establishing required component and system models is still evolving, a fully numerical development loop will largely depend on test data. The following functions of test data can be highlighted:
- Benchmarking and system target setting
- Reference model verification

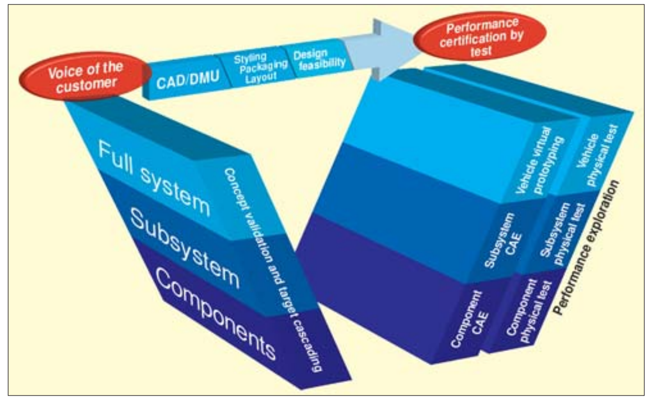

Figure 4. Product engineering in the V-process.

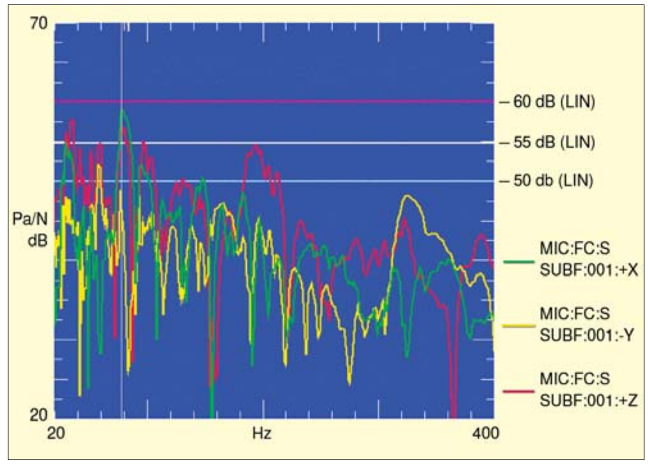

Figure 5. Body-noise FRF benchmark.

- Load analysis and definition
- Component, subsystem and system model verification and updating
- Hybrid model building
- Design verification and product qualification
- Human response assessment

Each of these functions will be briefly reviewed.

Benchmarking and Target Setting

Before the design of a new product is started, performance specifications must be defined. Such specifications can be expressed in a variety of parameters, ranging from total interior noise level to system characteristics like the first torsion mode in a car or first engine suspension mode in an aircraft.

An accepted approach is to test competitor products of the same category and to analyze earlier product versions. This provides information on achievable performances and also allows investigating which of the parameters is expected to be a bottleneck in the design. Not only operating response values need to be measured, but also transmission quantities and system properties, leading to an indication of critical subsystem performances. These data offer the basic platform to specify required product behavior in terms of global system and detailed subsystem targets. An example benchmark of body-noise frequency response functions (FRFs) is shown in Figure 5.

Table 1 shows an example of the benchmarking of two vehicles with respect to dominating noise sources. Car 1 reflects the benchmark (target) vehicle, while Car 2 denotes the reference vehicle from where the new design starts, indicating critical noise paths and frequencies.

In these evaluation studies, perception aspects related to sound quality or ride comfort are important to properly map the customer's viewpoint and to relate this to objective measurable quantities. Targets for these parameters can be derived by applying response manipulation methods (e.g., data filtering for subjective sound quality assessment).

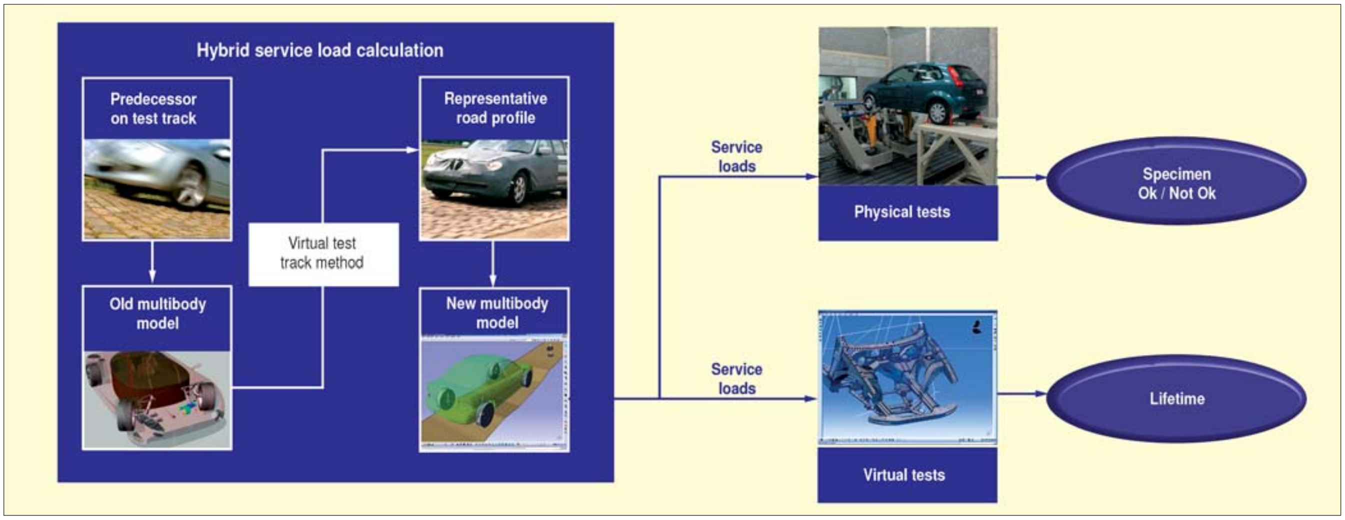

Figure 6. Benchmarking for noise path contributions.

An important aspect in ‘mapping’ product behavior (and target derivation) is assessing dependency of performance as a function of various operational conditions encountered during the life of the product. Very often, performance evaluations are done in only a few standard test conditions (e.g., for a car: idle, standard run-up, etc). But a full mapping of performance indicators as a function of relevant operational parameters (such as torque level and engine speed simultaneously) allows identifying critical operating regions that are not always obvious otherwise. When identifying the corresponding system loads for the operational ‘space,’ virtual operating models can be developed.

Reference Model Verification

Many product designs do not start from scratch but use a predecessor or a platform-variant product as a starting base. While large modifications will obviously be made, the fact that an earlier physical system and numerical models are available will allow much faster derivative models for a new version. Therefore, it makes a lot of sense to first establish a very accurate numerical model for the reference product by validating and updating it with a detailed experimental analysis. This is mainly true for structural finite-element models (FEMs), which will be the basis for many other simulation purposes.

This reasoning not only holds for the system level, but also for the subsystem and component levels. In many new designs, subsystems or components from earlier designs will be reused. This advantage must be translated into providing the most accurate models for these components, considerably reducing the uncertainty of predicting global system behavior.

The first development stage, once the targets are defined, consists of evaluating basic design options at a concept level.

Table 1. Benchmarking for noise path contributions.

Partial Response	Car 1 Acoustic Response Rough Road (dBA) 1/3 octave bands									
	20	**25**	**31.5**	**40**	**50**	**63**	**80**	**100**	**125**	**160**
Path 1	43	52	43	49	48	47	53	57	54	49
Path 2	41	53	41	51	54	62	70	64	62	54
Path 3	43	52	44	50	48	43	56	56	58	53
Path 4	41	53	41	51	55	62	70	66	64	56

Partial Response	Car 2 Acoustic Response Rough Road (dBA) 1/3 octave bands									
	20	**25**	**31.5**	**40**	**50**	**63**	**80**	**100**	**125**	**160**
Path 1	35	44	40	44	57	47	55	56	50	44
Path 2	39	49	48	55	55	51	63	59	53	42
Path 3	34	43	41	46	57	47	47	51	55	49
Path 4	39	49	48	55	54	48	65	60	54	46

Simplified models derived from the reference model can be used. Starting from a validated reference model on an existing product is clearly an advantage. Using the reference model, the system-level targets defined above can be further propagated to the subsystem and component level. This process is called “target cascading.” While it is clear that the actual behavior of the system to be designed will be influenced by a complex interaction between its components, the subsystem and component targets derived from the reference system are the best possible assumption at an early design stage.

Load Identification

Simulations typically predict the response (acoustic, vibration, motion, etc.) for a ‘unit’ load acting at a single degree of freedom. While this provides qualitative insight into the intrinsic system behavior, this does not help the design fit the quantitative targets. Understanding what the critical operating loads are, and describing these in terms of location, level, and spectrum, is essential to performing meaningful response predictions and a true system optimization.

While to a certain extent, simulation methods are explored to this purpose (e.g., combustion/structural models in a car engine, aero-elastic loads on an aircraft), targeted tests on existing products are presently the most reliable (and very often the only possible) way to obtain this information. Dedicated transducers or even complete measurement systems have been developed, such as 6-DOF (degrees-of-freedom) wheel-force or wheel-position transducers. In many cases, the external loads cannot be measured directly, and specific indirect procedures (possibly even involving partial numerical models) must be used to identify and characterize the main (critical) loads.

An example is identifying static and dynamic loads on flap-and-slat tracks in aircraft wing subsystems. Strain measurements performed at accessible track parts are combined with an FEM for the track, leading to external loads at reference locations, such as a leading edge.

An important question related to loads obtained on an earlier or variant product is their invariance (or known dependency) with respect to the design adaptations made. An example is the derivation of “road profile” inputs to durability models, leading to a true “virtual test track,” or internal engine forces for a given engine type. Scaling of these quantities is often used to emulate adaptations in the loading subsystem, but the extrapolation of obtained loads (and their invariance) is limited to a range of vehicles. These loads are then used as inputs for numerical simulations or physical tests (Figure 6).

Simulation Model Verification

Once the first prototypes become available, tests are conducted to validate and update available numerical models. This happens first for the components and subsystems, but eventu-

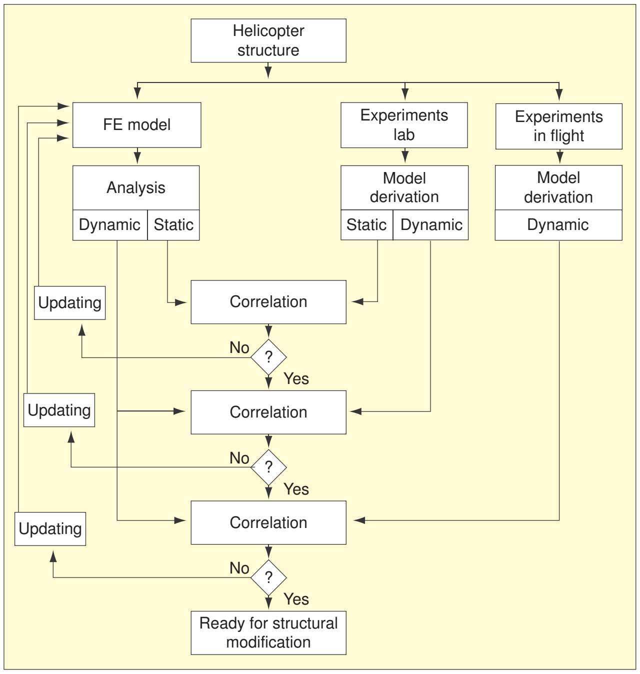

Figure 7. Helicopter finite-element model refinement process.

ally a complete system prototype is subjected to a full-scale evaluation. Examples are car body-in-white models, which need to be fine-tuned with experimental modal analysis before being integrated into full-vehicle models. There is also the ground vibration test (GVT) to validate (and update) aircraft finite-element (FE) dynamic models. Such validations are essential in view of aero-elastic simulations, which are made based on the FE model.

In practice, one typically uses static tests to update static FE models, laboratory modal tests to update dynamic models, and (although not yet standard practice) operational modal analysis tests to adjust the parameters of models for nonlinear elements such as joints, bushings, etc. Figure 7 illustrates a helicopter FE model refinement using both GVT and in-flight data.

The principle of numerical model verification and updating is not restricted to structural analysis. Vibro-acoustic numerical models need to be verified by means of acoustical or vibro-acoustical FRF tests or standardized response tests. The latter is critical for the correct assessment and generation of the source strength used in the tests, which leads to the issue of load identification. The use of calibrated acoustical sources is key to correctly address this problem.

When extending this to the verification of simulation models for vehicle dynamics, dedicated equipment for measuring displacements and also rotational motion is necessary, and dedicated multibody simulation validation and updating procedures need to be established.

Hybrid modeling

While low-frequency FE models of bare metallic structures tend to adequately describe the actual structural dynamics, this is far from true in the higher frequency range and for built up structures with complex connections. Experimental data are extensively used to provide direct input for critical model values such as material parameters related to structural or acoustical damping, acoustic absorption, impedances, etc. Specific test procedures and equipment are used. Also the interconnection between various substructures is extremely difficult to model. An approach is to derive these parameters from FE validation tests, where updating the model is confined to critical parameters.

But the 'marriage' between test and analysis occurs on even more advanced levels. At a specific point in development, numerical models of new subsystems or components can be combined with test models of existing subsystems. This approach is referred to as 'hybrid' modeling. With analytical FEMs, the corresponding substructuring approach is already common practice, but combining test and FE data is less straightforward. Depending on the frequency range, experimental modal analysis (EMA) or analytical modal analysis (AMA) models are used, with specific requirements for the nature of the test data needed (e.g., measurement of rotational DOFs, of rigid body parameters, of residual modes, of local stiffness at coupling points, etc.).

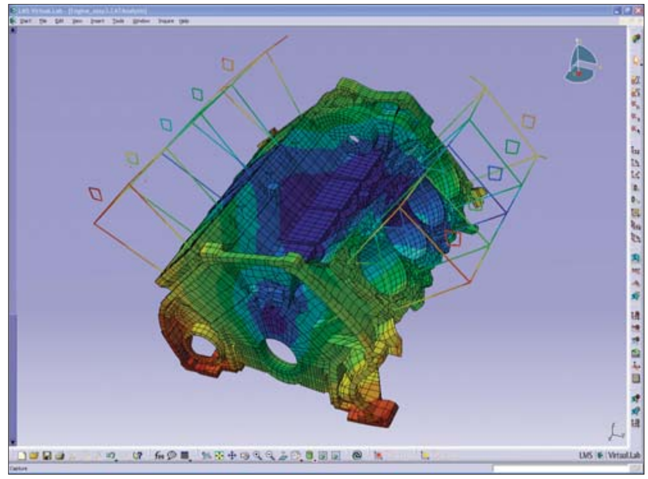

Figure 8a. Hybrid engine model.

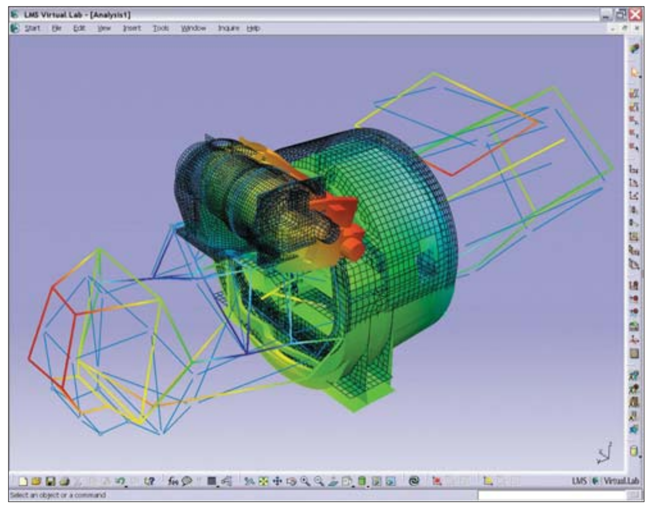

Figure 8b. Hybrid compressor group model.

Figure 8 shows two hybrid substructuring cases. In Figure 8a, an engine block is modeled by finite elements, while several added components are modeled by test data. Figure 8b concerns an industrial compressor group, where a new gearbox (FE) is to be coupled to an existing motor and compressor (available as test models).

The classical hybrid modeling case is where two or more structural components are combined, but a similar approach is applicable for structural and cavity subsystems. An analysis example is the calculation of critical panel contributions to interior car noise. When a trimmed-body, structural, FE model is available, it can be combined with experimental acoustic FRFs representing the cavity. Inversely (and perhaps more realistic), when a numerical cavity model is available, it can be combined with an experimental structural model to identify the most contributing panels for a given load (e.g., engine-induced, high-frequency vibrations). The measured FRFs describing the deformation of the structure for the given excitation are used here as velocity boundary conditions of the acoustic model (Figure 9).

Product Verification and Qualification

Once the first complete product versions become available,

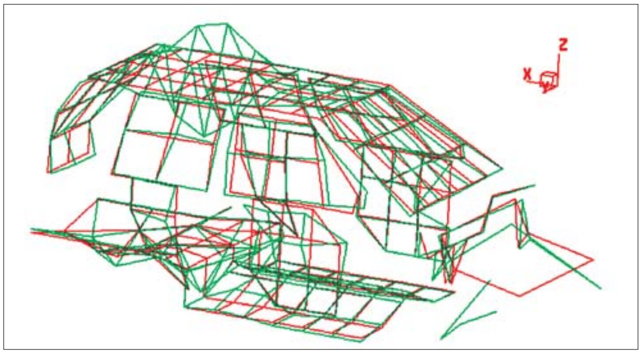

Figure 9a. Hybrid vibro-acoustic model – structural test modes.

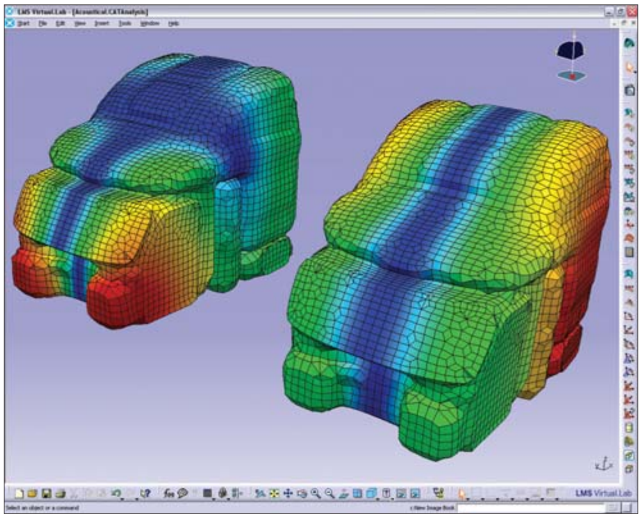

Figure 9b. Contribution to sound pressure at driver's ear using a cavity numerical model.

final testing for verifying actual product behavior is performed. This testing is essentially focused on specific system-level targets for that product. This may relate to internal noise and vibration levels, strains at reliability-critical locations, etc. In some applications, such tests may take the form of official collocation or certification tests.

An example is a pass-by noise test for the exterior noise impact of vehicles, which is regulated by standards for cars and trucks. Another example is the opening of the flight envelope for aircraft, demonstrating that the aircraft is free from flutter for a specified envelope of speeds and altitudes. These tests are essential in the certification process of the aircraft, but their performance is not free from danger. Therefore, there is high demand for accurate and fast on-line data processing and rapid system analysis.

In many sectors, but especially in the space and defense industries, product qualification also implies verifying that the product withstands predetermined environmental conditions. Examples are the acoustic and structural loads experienced by a satellite during launch or loads experienced by an aircraft's sensitive avionics equipment during flight, taxiing, or landing. Specific testing procedures replicating operational loads or following international standards have been developed.

Product Lifecycle Monitoring

An application of testing not explored much until now extends the role of testing to monitoring product behavior during its lifetime. At present, only isolated and totally separate systems are available for specific applications such as monitoring rotating machinery. Recent research into structural monitoring using system models is advancing toward a fully integrated lifecycle testing approach, with first application in civil engineering and the aeronautics worlds, where structural integrity is clearly and directly linked to safety. In other applications such as noise and vibration behavior of vehicles, the

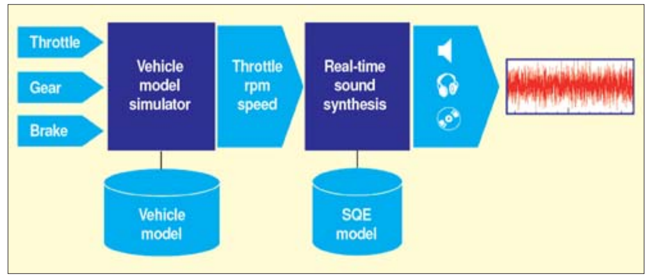

Figure 10. Virtual-car sound synthesis.

issue of lifecycle evolution of performance is not addressed yet, but it is clear that current evolutions in on-board electronics (also in cars) will make this technologically possible in the near term.

Introducing the Human Factor

Imperative in all designs is that products must answer customer expectations. The exact definition of these expectations and verification of the designs and design alternatives must explicitly take into account the subjective perception of product characteristics. Examples are the human responses to vibration and sound, which has led to detailed studies in the field of vibration comfort and sound quality. While a number of indices are available, in many cases, the only true verification can happen by subjecting real people (or a test jury) to an actual sound and/or vibration environment. The evaluation stimuli may be perceived directly in the vehicle, but in most cases, these are replayed in dedicated test environments, ranging from headphones to driving simulators. Key to all applications is proper correlation between jury test results and calculated comfort indices. Recent evolutions extend this approach to global drivability indices, taking into account all human/vehicle interactions such as the forces and motions at the vehicle/driver interfaces.

Once perception models are available, manipulating the test stimuli can then be used to analyze underlying signal and system properties, allowing design changes to develop. The ultimate goal is to generate stimuli directly from virtual product models. The current state of the art involves a hybrid approach, linking measured signal and source components to vehicle models. This includes not only vibro-acoustic system characteristics but also gear/throttle/speed relationships (Figure 10).

As a result, arbitrary road and operational conditions can be resynthesized in real time from a virtual-car sound model, allowing direct evaluation of individual source or path contributions and modifications.

New Challenges and Requirements for Testing

The discussion in the previous section makes clear that the role of testing is far from finished, even in the context of digital product development. The inverse is true. By critically analyzing the complete development process and assessing when data should and can be made available, new demands for testing have emerged. A well structured approach to benchmarking, target setting, model validation, model parameter input, hybrid modeling, etc., will contribute significantly to the overall goal of a faster, cheaper and better development process. It is also obvious that demands put on test procedures and test data are becoming much more severe than in the past. Just continuing to test according to traditional approaches, using traditional equipment and algorithms, will not properly answer this challenge.

Part 2 of this article will highlight the main requirements for testing according to this new paradigm and will describe how applied test procedures (operational data collection, modal analysis, acoustic testing, noise-source identification, etc.) have to be revisited in view of the new requirements of virtual prototype refinement.

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