A New Testing Paradigm for Today's Product Development Process – Part 2

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Modern product development increasingly relies on simulation methods to optimize functional performance. The test-analyze-fix approach of physical prototypes has moved to computer-aided, engineering-based, virtual prototyping. Contrary to the belief that this would reduce the demands for testing, it has opened new applications, new challenges and opportunities. Part 2 of this article covers these techniques.

(See page 14 of the September 2005 issue of Sound & Vibration for Part 1 of this article.)

The demands on speed and ease-of-use of testing procedures have become very severe. Testing a component, subsystem or full structure will always be in the critical path of the development project. The number of prototypes to be tested will certainly dwindle, leaving less time for each test. Furthermore, since the analyzed structure will be in use for other tests immediately after completion of the current one, it is essential that all necessary data are acquired and validated during the short period that the structure was available, leading to a "test-right-first-time" demand. With testing becoming a 'supporting' technical commodity instead of a highly specialized task, it will be increasingly delegated to technicians and operators instead of being performed by engineering specialists.

Test Definition

A modern modal analysis test can easily comprise more than 1000 degrees of freedom. In particular, when validating and updating finite-element (FE) models, a sufficiently dense grid of test points is needed. The FE model grid is much finer than the test, requiring a substantial reduction. Selecting a minimal set of needed test and excitation points and their location is very valuable in optimizing test efficiency. The FE model itself can be used for such a "pretest analysis," maximizing test efficiency, reducing test costs and limiting unavailability of the prototype.

Test preparation can even identify target modes in view of the subsequent FE correlation to be performed. An optimal set of excitation and response nodes can also be identified for these modes. With aerospace applications in particular, FE models are always available before the tests are conducted and the tests are so expensive that a proper test preparation (and even "virtual test" dry run using the FE model) is a prerequisite before setting up actual instrumentation and testing.

In all applications, another tedious task is establishing precise test geometry. This also relies on the FE model and the capability of the operator to instrument exactly at predefined locations (which is unrealistic in most cases), or one has to measure the geometry of the test structure by hand. Novel methods are being investigated to reduce this time using coordinate measurement systems or an articulated arm equipped with electromagnetic or electro-optical sensing. Developed solutions include ultrasonic photogrammetry, grid projection and triangulation techniques. An example of the photogrammetry approach using a digital camera to measure the 3D geometry of an aircraft propeller is shown in Figure 1. The recently developed 'scanning' technique is very convenient and is based on linking each measurement location with an external reference frame through automated image processing.

Based on a paper presented at ISMA2004, the 2004 International Conference on Modal Analysis, Noise and Vibration Engineering, Leuven, Belgium, September 2004.

Test Instrumentation

The increasing complexity and size of the tests that are conducted mean that instrumentation setup takes up a significant part of the total test duration. State-of-the-art instrumentation consists of multichannel data-acquisition front ends with local conditioning, analog-to-digital conversion and signal processing connected to powerful computers. Channel counts range between 16 and 64, up to as much as 1000, depending on the application. Signal bandwidths typically range from 100 Hz to 20 kHz. Operational measurements require mobile systems, which in the case of large-scale structures like aircraft, need to consist of multiple, distributed, but time-synchronized units.

As errors in cabling and sensor identification become more difficult to be noticed and corrected, automated procedures, including the use of "smart transducers" with embedded information in terms of calibration, position, etc., become more widespread. The concept of a "transducer electronic data sheet," or TEDS, embedded in the transducer is covered by the IEEE 1451 standard.

Another important efficiency gain is that the structure under test can be pre-instrumented (including sensor calibration) outside the test room. The sensor 'remembers' its location, calibration factor, history, and identification, only requiring 'blind' cable connections to start the actual test. This optimizes the occupancy and throughput of costly test rooms (for example, semi-anechoic rooms for studying vibro-acoustic effects) and significantly reduces cabling errors.

Test Data Plausibility Validation

The key concern with acquiring test data is that these data must be valid. Errors in the setup or during the test must be detected and identified before the test is closed and the setup dismantled. Often there is no second chance to redo part of the tests, and this would be very expensive and disrupt the testing schedule. "Testing-right-first-time" is the paradigm. Detecting test data problems has to be done on several levels:

- Transducers: Are they properly connected to the structure? Are they properly connected to the test system? Are they functioning properly?
- Are the test conditions in accordance to the specifications (excitation, engine speed profiles, references, suspension or boundary conditions)?
- Is the quality of the measurement signals adequate (levels, spectrum, linearity, noise, digital signal processing (DSP) errors)?
- Is it possible to automatically correct identified errors or test data problems (drop-outs, bias, drift, spikes)?
- Can problem areas be easily identified in terms of structural locations, frequency ranges, and test conditions?
- Is the consistency between the signals adequate in view of the analysis – correlations, coherences, frequency response functions (FRFs), etc.
- Are preliminary, on-line, analysis results available to monitor the test process (RMS levels, coherences, statistical parameters, order curves, modal parameters).

To yield data with maximum usability, indicators regarding the various test plausibility factors have to be defined, calculated, and monitored on line. Deviations have to be immediately recognized, and decisions must be made on whether to redo part of the test, correct data afterward, or just flag data as being invalid or with decreased plausibility. Time can be so

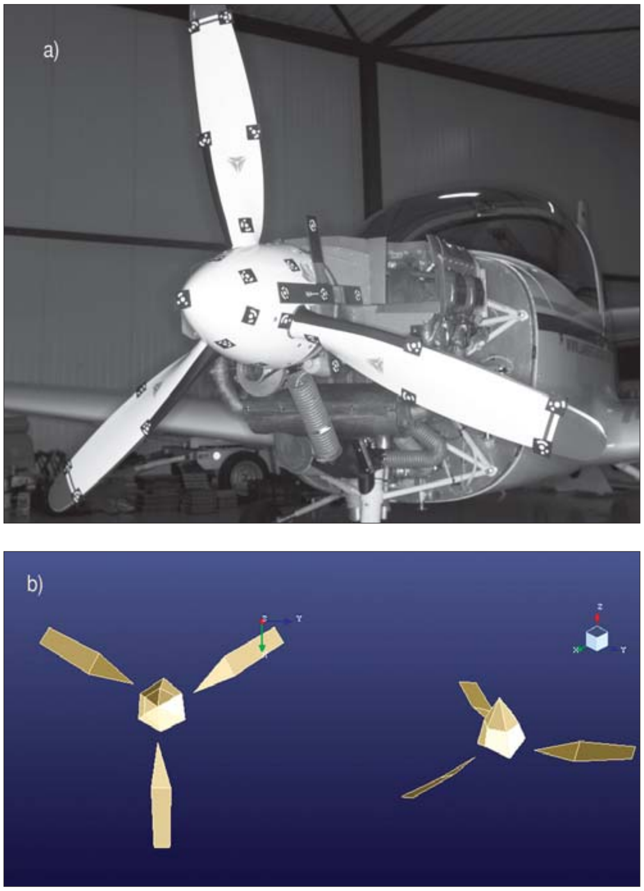

Figure 1. (a) Aircraft modal test setup. (b) Aircraft propeller geometry from photogrammetry.

limited that redoing the test (even partially) is not feasible, but at least one should not use (or use with caution) any 'flagged' data.

Essentially, it boils down to providing test engineers with easy on line and postanalysis data validation tools. Upon completing the test, a report with an assessment of the test data plausibility should be available. Figure 2 shows a global coherence plot, projecting FRF coherence on the geometry.

Optimal Data Exploitation

Most current applications either provide on-line measurement of dedicated functions, or the data are stored on some recording device for deferred processing. In the latter case, this is done because of safety reasons or because of insufficient on-line processing capability.

Directly linked to the requirement for condensing test programs are requests from test performers to combine on-line processing with storage of raw test data for later processing. This is necessary so that analyses can be done using other parameters (frequency resolution, order analysis methods, in depth time-domain analysis, for example) or to launch additional analyses without having to set up a new test. The considerations are similar to those discussed above for data validation: minimal use of lab time, minimal constraints on the testing routine and minimal test time. In-flight tests or jet engine tests are very expensive and the total number of such tests should be minimized to get as much information out of a single test as possible. In some cases, as with aerospace vibration testing, it may even be impossible to set up a second test, since maximum loading requirements were depleted in the first test. Also, for systems with a time-variant behavior (temperature effects due to heating of an exhaust or of an engine, for example), redoing a test in comparable conditions involves long delays related to cooling the structure.

The solution is to store the raw time data using the data processing system. In the case of an in-flight test, this requires

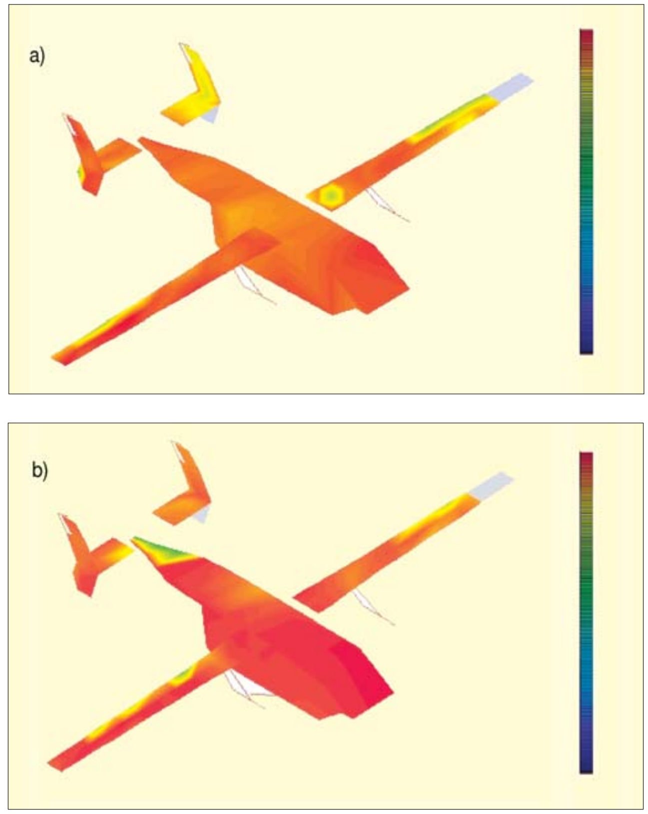

Figure 2. (a) Overall coherence value. (b) Coherence in critical frequency band.

high-speed data capacity up to tens of gigabytes of data. Adequate acquisition settings must be used to cover not only the current analysis requirements, but also those of potential secondary uses. In engine testing, this may lead to conflicting requirements on the level of sampling (octave band analysis, engine order tracking analysis and narrow-band spectral analysis) necessitating a return to applied methodologies.

Automated Analysis

A further concern with test data analysts is that many processing techniques are very user intensive, requiring interaction with expert users. Modal analysis is a typical example, requiring the selection of several analysis parameters and the interpretation of stabilization diagrams. This complex process is needed to isolate mathematical poles from physical system poles and to assess the 'uncoupling' of individual poles. While this procedure proves to be adequate for interactive selection of valid system solutions, the challenge is to automate the process. For systems with clearly isolated poles, this is addressed by rather simple methods, but for systems with coupled poles, this is still an open question. Researched solutions include: estimation methods that are much more robust with respect to the appearance of spurious poles; fully automated, self-tuning, algorithms such as the maximum-likelihood estimator; and also implementing heuristic pole selection rules in an automated procedure. The objective of the latter solution, for example, was to automate the modal identification that has to be done on each Space Shuttle after landing. While a full automation of this measurement process still seems too ambitious, it would be a major achievement.

An example of applying a more robust parameter estimation method, such as the LMS PolyMAX (least-squares complex frequency domain) method, is shown in Figure 3 where a ground vibration test (GVT) analysis of an aircraft is presented. The LMS PolyMAX stabilization diagram is compared to the standard LSCE (least-squares complex exponential) results. The clearer stabilization behavior and reduced analysis complexity is obvious.

Future research will involve both intelligent decision and learning mechanisms for capturing the user's expertise and fundamental investigation into the nature of mathematical poles and identification criteria.

Data Quality and Consistency

One of the most involved aspects of the new role of testing is that much higher accuracy is expected from experimental data. Key to this is that test results are not only used to perform a qualitative analysis or troubleshooting, but also that these data will contribute to building hybrid models. All test aspects related to data quality (which is something different than the basic validity of the data) have to be treated seriously. This involves constraints induced by boundary conditions of the test (suspension influences, location of rigid body modes, shaker-induced nonmeasurable secondary loads such as moments or lateral forces), influence of transducers, noise levels on orders or FRFs, leakage errors, frequency resolution limitations and so on.

A key problem often originates from the lack of consistency between the data due to small shifts in setup constraints, different mass loading, or temperature variations. While these errors are minor and would perhaps not really affect the quality of each individual measurement, global processing of these data may be subjected to severe errors. It is recognized that in FRF substructuring, the frequency inconsistency between individual FRFs is one of the major errors.

Automated procedures are being developed to integrate modal estimation results from slightly inconsistent data patches. The rationale is that small changes in some global modal parameters may be far less influential for the end result than the inconsistency itself.

Service Load Simulation

Testing of a vehicle – test drives on public roads and test tracks – is still the ultimate challenge for vehicle performance. For durability, such tests can become very expensive and time consuming, and significant gains can be obtained by simulating the measured service loads in a laboratory environment consisting of multi-axial test rigs.

The advantage of simulating service loads on a multi-axial test rig in a laboratory environment is that it allows testing 24 hours a day, 7 days a week, without a driver in the car and without adverse influence from weather or traffic. It offers much better surveillance of the test and an earlier detection of fatigue cracks.

A major advantage of the service load simulation approach is the possibility of running the durability test with compressed target load time histories that preserve the same damage potential as the originally measured signals. This so-called "*fatigue-sensitive data reduction*" dramatically reduces the length of the target signals and therefore also reduces time spent during the service load simulation phase.

Compared with test track durability testing, another major advantage of service load simulation on test rigs is that it is possible to run a more "customer-relevant" durability test. In an attempt to speed up testing, special test tracks have been designed to accelerate the test program by focusing on the fatigue-relevant 'events' and by omitting smaller nondamaging load cycles. However, fatigue loading on test tracks is often significantly more severe, certainly in terms of maximum amplitudes. Such a generic test track cannot be "customer relevant" for all types of cars and drivers. As a result, test track driving is mostly used for design optimization, during which different designs are compared to each other with respect to durability performance. On the other hand, service load simulation testing allows a more realistic durability test program by running an optimized mix of test track subsections. Figure 4 shows the setup of such a multi-axial test rig.

Similar approaches are adopted for noise and vibration comfort studies. Figure 5 shows a high-frequency, 6-degree-of-frequency (DOF) test platform used for suspension and road noise testing at Katholieke Universiteit Leuven.

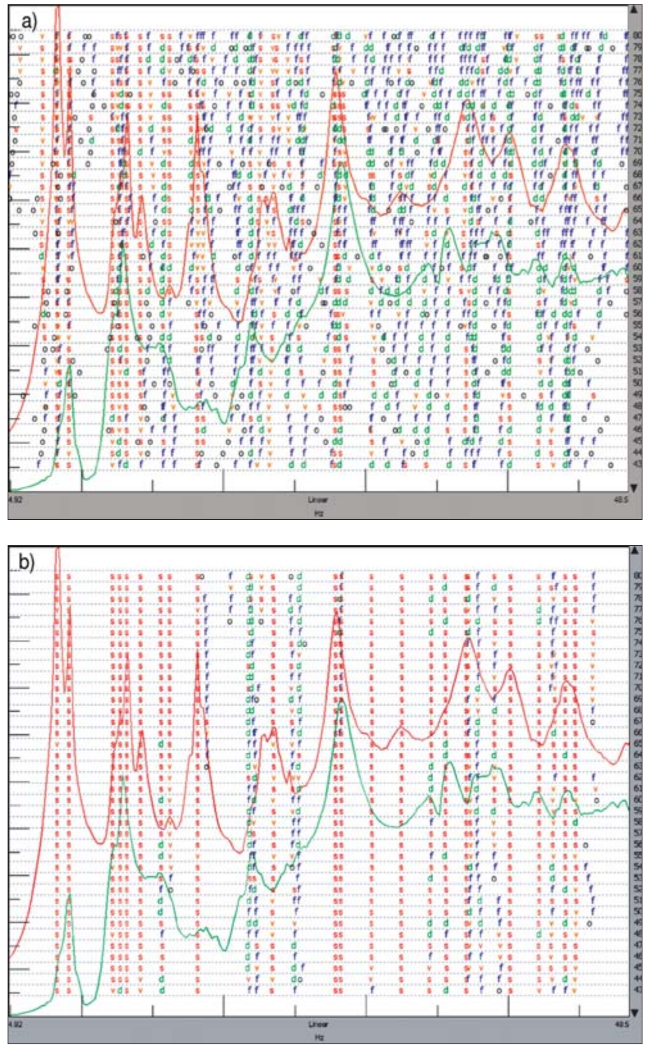

Figure 3. (a) LSCE stabilization diagram. (b) LMS PolyMAX GVT stabilization diagram.

Figure 4. Multi-axial test rig for service load simulation.

On the level of NVH or human comfort testing, research is conducted to synthesize mission-equivalent test conditions representative of the original road data in the relevant metrics. Next to the process improvements discussed above, it is essential to make testing fit the requirements of today's advanced

Figure 5. Six-degree-of-frequency shaker table vehicle setup.

applications. Some specific innovations have been introduced, expanding the limits of structural testing and making testing specifically fit the needs of virtual prototyping.

Optical Measurements

One of the instrumentation constraints with modal analysis is the effect of the transducer mass on the structure. With increasing frequency, the influence of transducer mass increases (larger inertia effect), while the number of transducers has to increase (higher spatial complexity of the modes). Noncontact optical vibration measurement techniques have been developed to counteract this problem.

Essentially two approaches are used. One is based on laser Doppler vibrometers (LDVs), which sequentially scan the vibrating surface. This approach supports broadband and sinusoidal testing, is integrated in standard test systems and procedures and is frequently used. The second approach is based on full-field electronic speckle pattern interferometry (ESPI). This approach uses continuous-strobe or pulsed lasers and requires use of sinusoidal excitation. The imaging takes place using a special charge-coupled-device (CCD) camera. Specific image processing transforms the qualitative interferograms to quantitative FRF values at the excitation frequency. The complete FRF is then built up frequency by frequency. Special data reduction methods allow reduction of pixel density vibration response fields to the spatial resolution needed for a proper modal analysis. The first industrial applications of this approach on cars have been documented.

High-frequency modal analysis or response analysis is essential when studying vibro-acoustic problems. Structural modeling at acoustically relevant frequencies is not straightforward, and for trimmed structures, not many successful applications are documented. Updating the structural models by test or using the test models in hybrid combination with numerical acoustic models is a practical alternative.

Vibro-Acoustic Modal Analysis

In many interior noise problems, not only the structure but also the cavity may show resonance behavior – such as the 'booming' noise in a car where a cavity resonance is excited by engine or road-induced vibrations. The concept of modal analysis can also be applied to acoustical or mixed structural acoustical systems using a volume velocity source as the acoustical input variable and sound pressure as acoustical output. Unique to this approach is that the eigen values are due to the coupled behavior of structure and acoustics. In general, they cannot be separated in a purely acoustical or purely structural cause. The eigen vectors, of course, each have a specific acoustic and structural part. Special scaling considerations related to the vibro-acoustic reciprocity principle have to be taken into account. Figure 6 shows an example of an acoustic mode of a car interior.

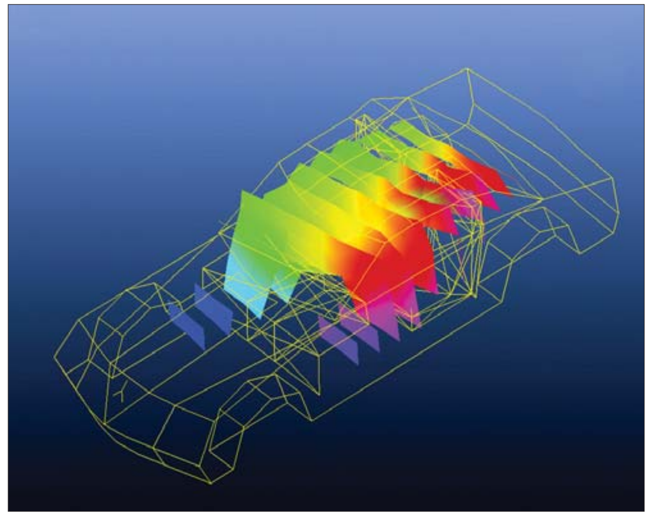

Figure 6. Acoustic mode shape of an automobile interior.

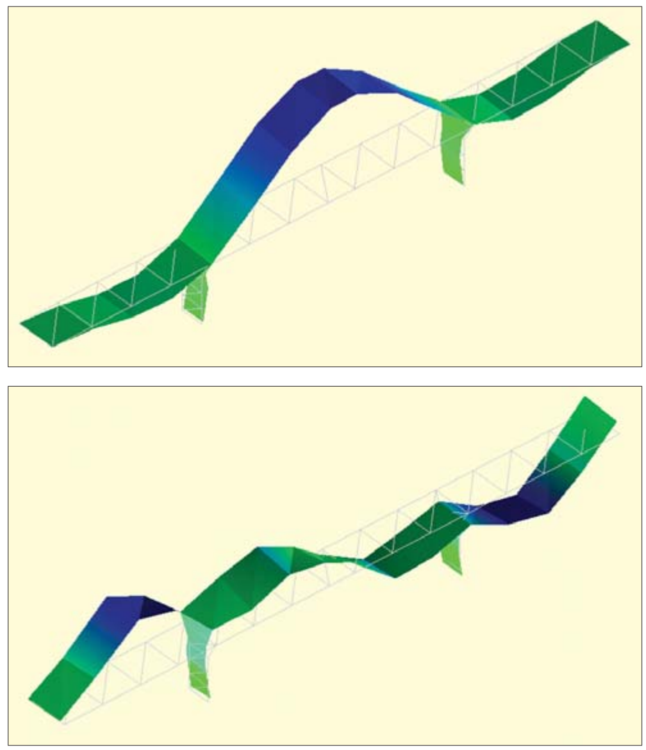

Figure 7. Two mode shapes of bridge output-only data.

The acoustic pressure in the measured vehicle sections can be represented by gray levels or color scales or by wire-frame motion. The modal behavior is clearly seen.

In-Operation Modal Analysis

In the classical modal identification approach, the baseline data that are processed are FRFs or impulse responses (IRs) measured under laboratory conditions. But in many applications, real operating conditions may differ significantly from those applied during the modal test – thus the need to derive models in real operational conditions. Since all real-world systems are nonlinear to some extent, the models obtained under real loading will be linearized for much more representative working points. Additionally, they will properly take into account the environmental influences on system behavior (prestress of suspensions, load-induced stiffening, aero-elastic interaction, etc.).

Another characteristic of in-operation modal analysis stems from the fact that in many cases (swell excitation of off-shore platforms, traffic/wind excitation of civil construction), forced-excitation tests are very difficult to conduct, and operating data are often all that are available. Therefore, a considerable interest exists in extracting valid models directly from operating data. Finally, in many cases (car road tests, aircraft/spacecraft flight tests), large in-operation data sets are measured anyway for level verification, for operating field shape analysis, and other purposes. Extending classical operating data analysis procedures with modal parameter identification allows a better exploitation of these data.

Only response data are measurable in most cases, while actual loading conditions are unknown. Consequently, over recent years, several modal parameter estimation techniques have been proposed and studied for modal parameter extraction from output-only data. They include auto-regressive moving averaging (ARMA) models, natural excitation technique (NexT), and stochastic realization methods. The approach is becoming well accepted in the industry. Recently the LMS PolyMAX method was also extended to output-only data. Figure 7 shows mode shapes from a test on a highway bridge excited by the wind and traffic. Despite the low vibration levels and the fact that only response data were available, the resulting mode shapes are of high quality.

Testing for Hybrid Modeling

Some final considerations can be devoted to the fact that hybrid modeling requires its own specific test results. The classical Craig-Bampton approach using fixed interface modes and static modes is not applicable when using test data. Hybrid approaches are based either on FRF substructuring or residual flexibility methods. The latter approach is based on free-interface modes, a condition fulfilled by standard modal tests but that requires additional, dedicated tests for rigid-body modes and residual flexibility modes.

The residual flexibility modes are necessary to model the effect of truncated higher modes affecting (dominating) local stiffness at the coupling points. This is shown in Figure 8, evaluating the effect of a modal resynthesis of an FRF before and after accounting for residual stiffness.

The modal truncation problem can be overcome by estimating residual modes (or pseudo modes) from static and dynamic compensation terms. Much improved results are obtained by including these residual modes in a conventional modal synthesis calculation. New methods to estimate the residual modes from measured FRF data have also been developed. An example of a hybrid substructuring calculation on a part of a vehicle assembly is shown in Figure 9, comparing the assembly FRF after combining two substructure models before and after including residual modes. Also, specific procedures based on a standard modal analysis have been developed for the experimental establishment of actual rigid-body modes and inertial parameters (center of gravity) of a structure.

Another example is the increased awareness of the effect of rotational degrees of freedom. These quantities, which are traditionally neither measured nor used in experimental models (modal analysis), play an important role in numerical calculations. When combining experimental and numerical models, their influence must be assessed, and dedicated measurements need to be made where needed.

Conclusions

The pressure on shifting product performance optimization to earlier stages of the development process has been relieved by a revolution in computer-aided engineering methods, resulting in a virtual-prototype engineering approach to product development. But contrary to the belief that this would eliminate testing from the development process, this has resulted in new demands for testing that are more stringent than ever. While testing was traditionally executed in a context of "test-analyze-and-fix" strategy, experimental data collection and analysis are now integrated throughout the various phases of the virtual product development process, from benchmarking and target setting through component model validation to establishing true hybrid product models.

Test data are no longer retained in isolated islands of excellence, but play an essential role throughout the development process and are used throughout the extended organization. This requires that each of the applied test procedures (operational data collection, modal analysis, acoustic testing, noise source identification, etc.) has to be critically revisited in view of the new requirements of virtual prototype refinement. S&V

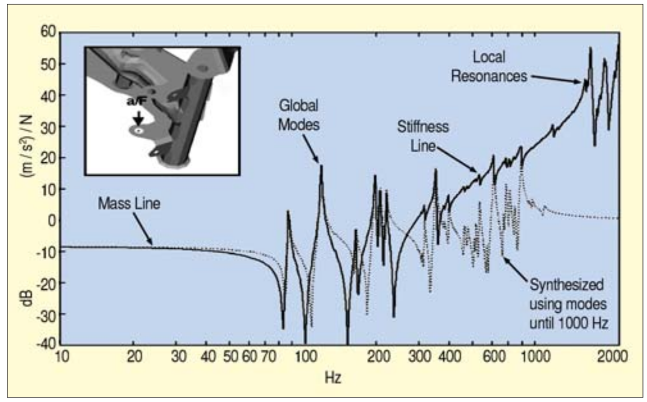

Figure 8. Effect of residual modes on modal synthesis calculation.

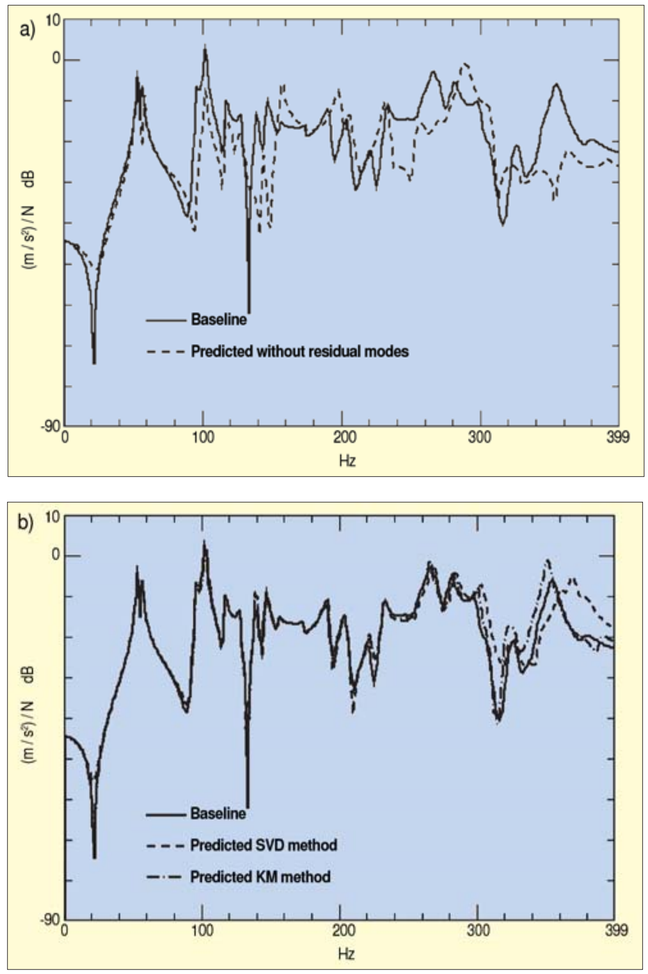

Figure 9. (a) Predicted FRF without residual modes. (b) Predicted FRF with residual modes.

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