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Automated Toolboxes for Target Setting, Troubleshooting, and NV Performance Prediction

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ABSTRACT

The role of NVH test development has changed from addressing a system-level NV concern late in the design cycle (firefighting) to having well established NV optimized test procedures in place. One way this is achieved is by leveraging the information gained during troubleshooting of current product to improve the future product development process for noise and vibration. Today, most NV groups/laboratories use optimized test procedures for creating accurate, consistent, and efficient test results. This still requires expertise to post-process data, compute targets and interpret results to guide product development. This step is often overlooked and, in recent years, due to the lack of NV expertise of "younger" labs (typically in non-automotive industries) or of more established labs affected by the economic downturn (early retirements, lay-offs, especially in the automotive industry) there has been a growing need for automated post-processing "intelligent" procedures. This paper describes a few automated software tools that have been developed by the authors to address common needs of different industries such as reducing post-processing and calculation time, interpreting test data, providing guidelines for further troubleshooting and predicting system performance from component-level data. The paper will also discuss the technique/process strategies used to develop such automated tools.

INTRODUCTION

The need for streamlined test procedures for systems and components emerged in the automotive industry in the early to mid '90's. Other industries also adopted standard test procedures for routine validation of their products, such as sound power testing of fans and compressors, among others. In response to this market need, commercial noise and vibration test software and hardware manufacturers added programming capabilities to their offerings to enable Noise and Vibration labs to execute efficiently these standardized tests. During the same time, other generic programming environments, such as LabView and Matlab, were also used to automate test procedures, data processing and report production. Over time, these tests, originally developed by R&D engineers for the R&D lab, have been reduced in scope (less transducers and signal processing) and migrated to the production floor for quality sampling and control.

Over the past few years, the need has emerged for different types of automated toolboxes. A relatively new need that has emerged from the Noise and Vibration engineering labs is for test-driven processes to predict performance of components at the system level and, subsequently, cascade targets for components. Once the process is done "manually" by the expert NV engineer, often by using a redundant number of channels and by trying and comparing a few alternate methods, a minimally redundant process is identified that uses the simplest possible experimental data set. The data processing procedures and steps can also be automated, most often using a generic programming environment (Excel, LabView, Matlab).

Another altogether different need has also emerged, the need for toolboxes that "guide" a non-expert engineer to troubleshoot a noise or vibration concern. In the automotive and other industries, a lot of noise and vibration expertise has been lost during the economic downturn due to lay-offs, early retirement and so on. In other industries, traditionally less concerned with product/consumer noise and vibration issues; there is lack of noise and vibration expertise and a need for guidance in data analysis and interpretation for design of countermeasures. In both cases, the need is for a somewhat 'Expert System', that is a toolbox that guides the user toward gaining insight on contributions, from different noise and vibration sources and paths, to the final receiver (whatever this may be).

This paper describes some of the different toolboxes co-developed by and contributed to by the authors and discusses the challenges associated to their development, validation and deployment in the field.

TARGET CASCADING, SETTING AND VALIDATION

Automotive OEMs have been actively working to define in-vehicle targets from benchmarking activities. This is an on-going effort as targets evolve alongside with market offerings and changes to customers' expectations. Each vehicle OEM owns an extensive database of vehicles' performances which is used to set targets for and track the performance of their vehicles. While the format of the database is OEM-specific, the strategy that makes use of it is essentially the same across various OEMs and is illustrated in Figure 1. An example of how this process was implemented by a vehicle OEM is described in [1].

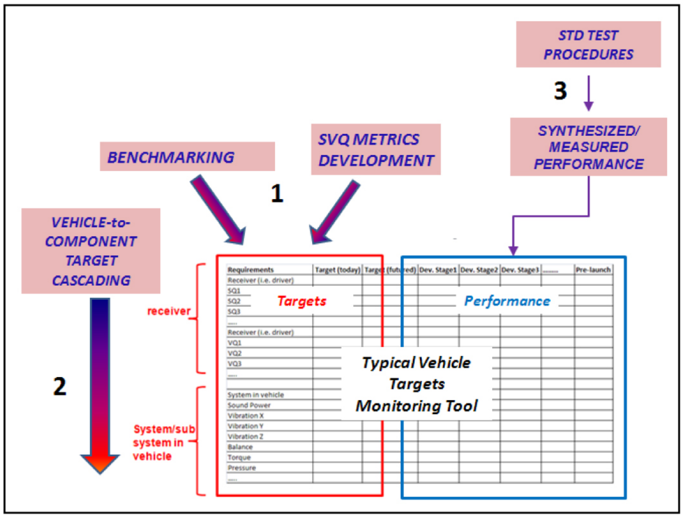

Figure 1. Example of Processes feeding the Vehicle Target monitoring toolbox.

Once targets at the vehicle level are established, these are then cascaded to sub-system and components typically by means of testing. For example, interior acoustic targets can be cascaded down to vibration targets of powertrain components. This activity is, in general, conducted with high-end exploratory noise and vibration tools, with a wide range of capabilities and high channel count. These tests focus first on the localization and quantification of the sources (with techniques such as sound power, sound intensity, and acoustic holography) and next on the identification of the paths (both airborne and structure-borne) with techniques such as noise path analysis and panel contribution analysis.

Due to market demand, more and more companies (most notably automotive suppliers) turned to customized software and/or test benches to efficiently and consistently test the performance of their product (component or sub-system). This market shift was a direct consequence of the target cascading trend. Once the target for the sub-system was established, the supplier was responsible for implementing the target in their product development process and then using it to validate design changes. These newly developed test procedures and algorithms to validate a product could also be then spread to company labs or manufacturing sites around the world.

From this growing demand for efficient testing at both suppliers and vehicle OEMs a new generation of efficient tools to automate testing and data processing was developed by tool's manufacturers. The new standardized testing utilized less high-end exploratory tools and more GUIs/automated data acquisition toolboxes, thus allowing for consistent testing within the lab and at remote locations. This also improved the efficiency of data acquisition tasks because test setup time was minimized and the process was streamlined to reduce the need for retests. An example of the transition from exploratory to standardized testing to production Quality Control is well illustrated by the papers in [2] and [3], where a SQ test procedure for powered seat adjusters developed by the R&D lab [2] was later simplified and deployed to the production floor [3]. On the production floor, it is important to run the minimum amount of tests to catch all identified failure modes while optimizing location and number of transducers. When the most representative simplified test procedure is implemented in production, and when the acquired data are properly managed and mined, the value is immense for both the manufacturing engineering side to improve process related issues and the product engineering side to improve design related issues.

TROUBLESHOOTING AND PREDICTING PERFORMANCE

The standardized tests described above are utilized today in the majority of industries, from automotive to consumer products, from appliances to off-highway and construction equipment and so forth. But in recent years a new generation of toolboxes have been needed and developed to supplement and/or complement the knowledge base of the engineering team. As explained earlier, this type of "expert system" is needed in cases where there is a lack of specific expertise in noise and/or vibration, yet noise and/or vibration issues often arise and are tackled late during the product development cycle.

The NV Troubleshooting Wizard

The term "Expert System" or ES refers in general to a computer program that attempts to mimic human experts by the system's capability to offer advice, teach, and execute intelligent tasks. In other words, a software that functions like an expert. The software toolboxes described in this paper are a long way from fitting this definition, as they are a very simple and even crude way of replicating the thought process of an expert. To be clear, in the context of current technology, the toolboxes described here are not even close to Apple's Siri personal assistant nor to artificial intelligence tools such as, as a recent example, those developed by the University of Rochester to create an artificial chat partner [4]. But they provide a thought process roadmap, a sort of a software wizard, that guides the user through several steps of data processing and that aims at facilitating the interpretation of the data.

The first such toolbox was co-developed by the authors and a team of their colleagues for an aerospace application. A typical problem encountered in complex optical systems, such as those used by telescopes and laser systems, is that of identifying root-causes of vibration-induced jitter in beam alignment systems. Line-of-sight (LOS) jitter is the apparent motion of a stationary object as viewed by an optical sensor [5]. Beam jitter is undesirable and software control strategies are widely used for its mitigation. However, to improve the efficiency and effectiveness of jitter control strategies, it is desirable to decompose the jitter induced by external disturbances (platform vibration, as an example) from the jitter induced by internal mechanisms, such as the motion of Fast Steering Mirrors (FSM) or other actuation mechanisms integral to the optics.

The toolbox developed for this application, called the Jitter Vibration Decomposition Toolbox, or JVDT, applies strategic measurement techniques and advanced signal processing algorithms to help the control and system engineers to quantify the jitter sources and paths in a consistent and accurate manner. The starting point was a series of high-channel count tests on a High Energy Laser system. Both operating and artificial excitation testing were performed with accelerometers mapping all accessible optical elements, pressure transducers acquiring dynamic pressure across the servo-valves (telescope gimbals were servo-hydraulic-actuated), angular rate sensors measuring azimuth and elevation, control and Fine Tracking Error signals all being acquired at the same time in the time domain.

The "manual" process followed by the authors, typical of any troubleshooting activity, is illustrated in Figure 2 and summarized as follows:

- Data inspection in time domain, time-frequency plots (3D), average FFT
- Due to the large number of transducers and potential sources, Principal Component Analysis was used to identify the number of uncorrelated sources in the system
- The low frequency content of candidate source channels was inspected by wavelet analysis
- Cross-correlation(t) was performed across candidate source and path "channels" to identify temporal causality
- Conditioned Input Analysis was then applied on a reduced set of potential inputs to evaluate uncorrelated contributions to the receivers (Fine Tracking Errors)
- Operating transmissibility and FRF from artificial excitation tests were then inspected to confirm likely sources and their % contributions to FTE

The JVDT toolbox was developed to mimic these steps and apply these different signal processing techniques in a sequential manner, as an "expert NV engineer" would do. Since these steps are not specific to a particular system or product, this type of semi-expert NV troubleshooting toolbox could be useful in NV labs as a preliminary "data screening and interpretation" tool for less experienced engineers.

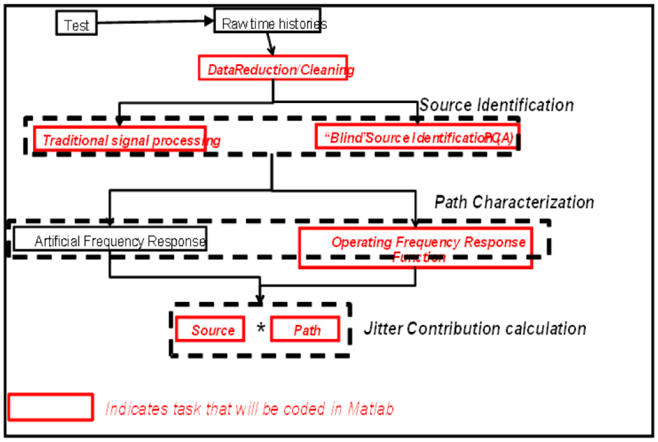

Figure 2. Jitter Vibration Decomposition process. Test task/data in black, analysis/software tasks in red.

The NV Synthesis and Target Setting Toolbox

A toolbox was developed for an automotive OEM as a pass-by-noise simulation tool that computes contributions from specific vehicle sources [6]. It should be noted here that, unlike in the previous scenario, in this case the users of the toolbox are expert NV engineers, who are very familiar with testing and signal processing techniques. Their need was for a more efficient way to perform pass-by noise testing and for an objective, data-driven, target development and validation procedure.

Operating noise measurements were made at all sources that significantly contribute to pass-by-noise like tire, engine, intake, and exhaust. Measured source data were combined with measured acoustic transfer functions to estimate contributions and overall vehicle pass-by sound pressure levels. Figure 3 shows an example of measured pass-by noise (A-weighted level versus vehicle position on the course) along with estimated contributions from several of the key noise sources. Once contributions were computed for each vehicle position on the course, FFT spectra were interrogated at the position of maximum pass-by level to assess the frequency and level of the dominant source(s).

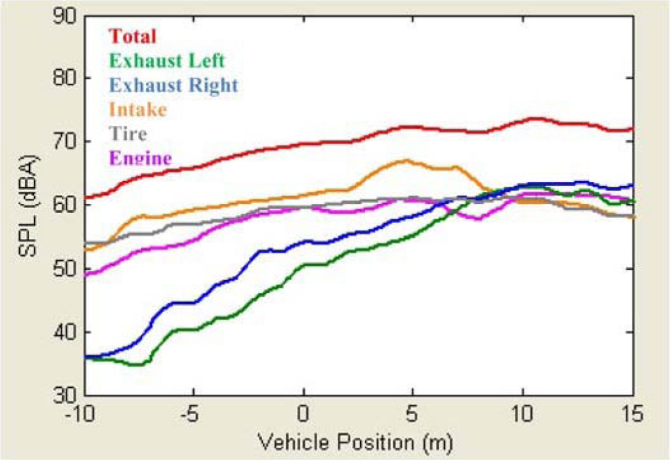

Figure 3. Sample Pass-by Noise Levels with Contributions

This information can be utilized in two distinctively different ways. First, if the maximum allowable pass-by level is exceeded, a target pass-by noise level can be specified and the required performance of any key noise source can be calculated to achieve this target. This information is valuable because it provides guidance for the engineering design teams for the required acoustic performance of a component, to which functional prototype designs, such exhaust muffler Insertion Loss, can be developed. This scenario is summarized in Figure 4, where Design A, B and C could be, as an example, alternate Insertion Loss performance for the exhaust muffler to achieve compliance to Pass-By specification.

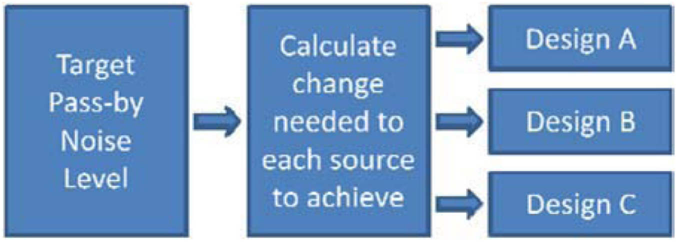

Figure 4. Component Design Criteria to Achieve Pass-by Target

The second toolbox utilization scenario is for evaluating design alternatives without actual hardware and/or testing. When designing components that have an impact on the pass-by noise performance of the vehicle, it is beneficial to be able to evaluate various design alternatives analytically to understand the expected pass-by noise performance for each. This information can help to include or exclude various design solutions for being pursued further by the engineering design teams. Figure 5 shows the opposite flow as the one shown in Figure 4. Here different designs of a vehicle source, such as, different Insertion Loss functions for the intake resonator, which can be theoretical (from acoustic models) or measured on an acoustic test bench, are fed to the toolbox to estimate the corresponding pass-by noise level.

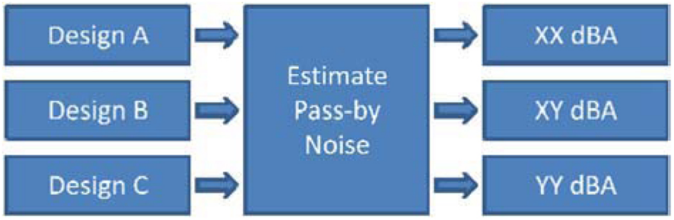

Figure 5. Estimation of Pass-by Performance from Design Alternatives

In either case a basic source-path-receiver model is used to characterize the acoustic radiation from each of the key noise sources on a vehicle along with their respective paths to the pass-by microphones. The result allows for the estimation of the overall vehicle-level pass-by noise along with the contributions to the total and dominant frequency content from each of the key noise sources. This synthesis tool provided the customer with a valued process improvement by reducing the amount of physical test time and aiding in the development of intake and exhaust systems for pass-by performance.

The SQ Prediction Toolbox

A toolbox was developed for an aftermarket tire manufacturer to improve their product development process for sedan and SUV product lines [7]. Tire Sound Quality is an important factor for customer satisfaction within the replacement tire market. Traditionally, tires are designed, created, and subjectively tested on a vehicle on the road. This presents the need for a method to objectively quantify tire noise as it exists from on-road excitation, as well as a tool to predict this noise (and therefore driver perception) from a component-level test. This toolbox was developed by streamlining this process by determining what made tire noise objectionable (Jury Test), and creating a preference equation so that measured sounds could be used to predict people's opinions. Then, a single-tire test stand was employed so that sounds collected could be synthesized into the sound that the same tire would produce on a vehicle on the road. A flow chart describing this process is detailed in [7] and shown here in Figure 6.

This toolbox is also used as a research and development tool to evaluate the impact on SQ of different tire design parameters.

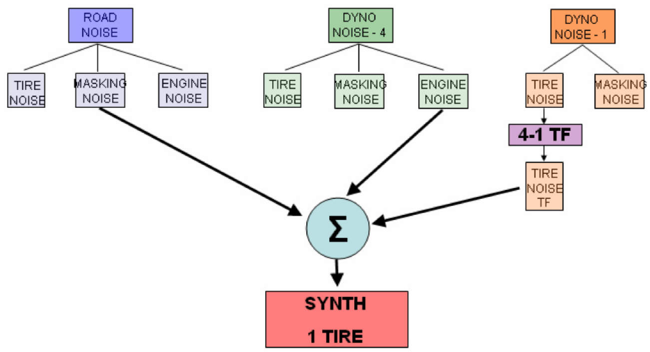

Figure 6. Block diagram of sound synthesis process to synthesize in-vehicle noise

CHALLENGES WITH BUILDING TOOLBOXES

The development of a “semi-expert” troubleshooting toolbox presents many difficulties. From [8], the major components of an expert system are:

- The knowledge base, that is the facts and rules of the system
- The Inference engine, which is the reasoning mechanism that tried to derive answers from the knowledge base
- The user interface that provides the “dialogue” between the ES and the user

Even without attempting to build any real inference engine, i.e. intelligence, in the system, it is challenging to frame the data and all other inputs in a way that truly represents the problem (knowledge base). This is even more complicated if the toolbox is expected to be applied to different systems. As an example, one of the challenges for the authors in developing the jitter troubleshooting toolbox is its applicability to optical systems which can be actuated by different mechanisms (servo-hydraulic vs. electro-magnetic). The other major challenge is to design a user interface which is understandable for a non-expert user and that summarizes essential information in easily understood formats (tables, Excel files, etc.).

Other challenges are encountered when transporting standardized testing into the production environment, as described by Pietila and Goodes [9]. The main challenges encountered relate to product, production, and customer. Within product challenges the major obstacle is identifying all failure modes associated to the product. Once these have been identified, location and number/type of transducers need to be defined to detect acceptable from unacceptable components.

The next common challenge relates to the production environment, for example understanding cycle time constraints. It will not be feasible to run a component that causes a bottleneck in the production process. Also, one needs to consider that the background noise and vibration levels on the production floor are higher than those in the laboratory environment. Another challenge is the performance of the test stand. For example, it is typical for a manufacturer to want to use an existing test stand even if it is not designed to evaluate NV performance. A functional tester may run the product in a completely different way than what is required for assessing NV performance, due to variables like load, speed, ramp rate, etc. The last common challenge relates to customer specification constraints. As an example, if the customer mandates for the component to be run exclusively per the specification, modifications to the test procedure may not be acceptable. In this case, additional test stands that perform more exhaustive testing may be added and their results correlated to the customer accepted test stands.

Finally, general software development guidelines can be grouped in four main categories:

- Develop requirements
- Design of software/toolbox
- Implementation
- Testing

The first task of developing requirements provides the list of functionalities that the toolbox will need to have before any coding takes place. This is critical because the requirements document will help the software development manager to stick to the plan minimizing the risk of “scope creep” during implementation. Requirements are defined by interviewing potential users who would use it, how to, what for, expected inputs/outputs). Also belonging to this task is the development of use cases, which will finalize specifications and define acceptance tests.

The second major task in software development involves the design of the toolbox, which details how the toolbox will work. In this task the architecture of the toolbox is developed, that is how it will handle hardware/software communications, and communication with the user via GUI (Graphical User Interface). Once requirements and software architecture and lay-out are defined, coding begins, according to a coding schedule with many intermediate milestones and checkpoints. The main challenge at this point is to ensure that issues are identified and discussed with the team in a timely manner so that countermeasures can be put in place without significant delays. As for the final code testing task, the main challenge is of devising exhaustive validation test sequences (signals and algorithms) that encompass the vast majority of the functionalities and modality of use.

In summary, there are several challenges in developing NV software toolboxes. These challenges are inherent to software development but they become even more evident when the software is designed and developed by NV engineers. In this case, the authors recommend the external support of a software development expert who can help the NV team to frame the problem and to develop schedule and guidelines.

SUMMARY/CONCLUSIONS

Over the last few years, a new trend has emerged in the noise and vibration lab, where automated toolboxes, often data-driven, are developed to predict performance and facilitate product design decisions up front. Shorter product development time in all industries means that engineers have to rely more on predictive tools. These can be entirely analytical, such as finite element or vibro-acoustic models, or could be data-driven, such as the synthesis toolboxes described in this paper, or hybrid CAE-test.

If a fully validated and representative CAE model is not available, tools that predict NV performance based on data from existing hardware and on inferences on the physics of the system can be a valuable alternative for the development engineer. They can also be used to validate CAE models and theoretical performance of specific components.

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DEFINITIONS/ABBREVIATIONS

NVH - Noise Vibration & Harshness
NV - Noise & Vibration
OEM - Original Equipment Manufacturer
ES - Expert System
GUI - Graphical User Interface
HEL - High Energy Laser
SVQ - Sound/Vibration Quality
R&D - Research & Development
LOS - Line-of-Sight
FSM - Fast Steering Mirrors
JVDT - Jitter Vibration Decomposition Toolbox

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