Practical Approaches to Solving Noise and Vibration Problems

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This article captures the strategies involved in addressing a system-level sound and vibration concern late in the design cycle. We start off with a discussion of the long-term goal of problem solving and the importance of leveraging the information gained during troubleshooting to improve the product development process for noise and vibration. A discussion then focuses on determining if the issue is due to nonconformance to a specification or a sound and vibration quality concern and how that information influences the problem-solving process. Baseline testing of the product is then reviewed, and test strategies are discussed to help identify the issue and quantify the sources and paths that contribute to the objectionable issue. A review of other problem-solving tools is included, and the article concludes with predicting the noise and vibration performance of a product and the role of test data in this process.

A noise and vibration problem often shows itself very late in the design cycle or even after the product has been released. This occurs for a variety of reasons, including poor target setting, lack of design consideration and lack of reaction to warnings. Problems occurring this late in the design stage are often costly to fix and have limited design solutions. The outcome of any troubleshooting investigation should not only be to resolve the immediate concern but also to feed that knowledge back into the design process so the concern does not happen again.

Noise and vibration issues can generally be separated into two categories: a problem caused by lack of compliance to a regulation or specification; or the product does not perform adequately *in-situ*, causing sound or vibration quality (SVQ) concerns. It is important to categorize the noise issue, because that determines the mode in which the product must operate when being evaluated.

Measurements are made on the product during the appropriate operating conditions, and focus is put toward characterizing the problem. Analysis that results in overall vibration levels or even third-octave band data, which are common for specification-type testing, are of limited use in fully understanding the problem. Significant care must be taken at this stage to correctly characterize the problem, since this is the starting point that the investigation will be based on.

Once the mode of operation is understood and the problem is characterized, testing to understand your product can begin. The goal of this part of the investigation is to determine the sources and paths within the product or system that contribute to the overall issue. An understanding of the sources and paths gives an understanding of the opportunities that exist to make design changes.

A variety of problem-solving noise and vibration tools are at the engineer's disposal: order tracking; modal analysis; noise mapping techniques such as sound intensity; near-field acoustic holographic and beamforming; and several others.

Long-Term Goal of Problem Solving

The obvious initial goal of noise and vibration problem solving is to resolve the noise or vibration issue. Unfortunately the issue often occurs late in the design cycle or after the product has been released, and the design envelope for alternatives is often limited and expensive. The long-term goal for problem solving should therefore be to identify and resolve the issues early. This is done through taking the information learned in the troubleshooting process and feeding it back into the design cycle as illustrated in Figure 1.

It is a well understood fact that the cost of design changes increases significantly throughout the design cycle. A design change to add a stiffening rib, a larger range of isolation or packaging space

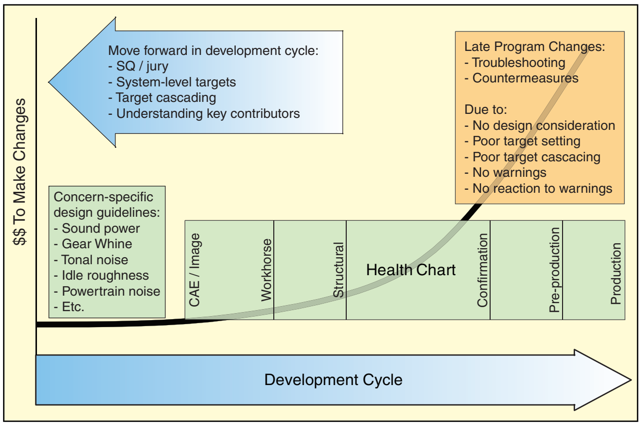

Figure 1. Improving the noise and vibration development cycle.

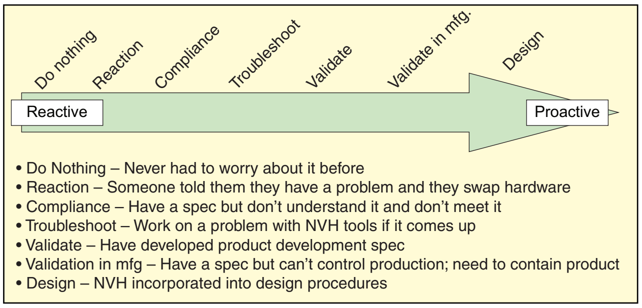

Figure 2. The noise and vibration maturity model.

for sound treatment can cost little to nothing at the early design stages of a product, before hard tooling is in place. As the design envelope closes throughout the product design cycle, the cost to make those same changes can be significant and are often done with compromises due to other design constraints.

Therefore, it is in a company's best interest to limit the number of design changes required late in the program. In a reactive mode these late program issues occur due to a variety of reasons such as lack of design consideration, poor target setting, no warnings and lack of reaction to warnings. To reduce the number of late program changes, a company needs to move its efforts forward in the development cycle using SVQ/jury, target cascading and understanding key contributors. Beyond design recommendations, these key contributors are the output of a troubleshooting investigation and can be leveraged to include or improve NVH performance in the design cycle.

For example, a product such as a compressor is often tested for acceptance by the customer based on a sound power specification. The response to failing such a test by the manufacturer is often to change the operating conditions to avoid specific speed ranges or to add damping or isolation material to reduce the amount of noise emitted. Neither of these is an optimal solution; one may have the product operating at less than optimal conditions and the other is a cost and weight increase. Through a troubleshooting investigation it became clear that the compressor housing had a resonance at a harmonic of the compressor pump at the operating speed. A simple design guideline to avoid this type of issue would have been to set a requirement for no housing resonances in the operating range of the pump based on the number of cylinders.

The output of an intensive troubleshooting investigation is concern-specific design guidelines that can be used as the basis for continuous product improvement on future designs. Performance

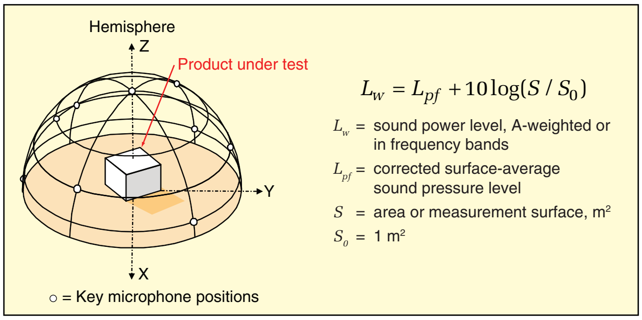

Figure 3. Sound power test example.

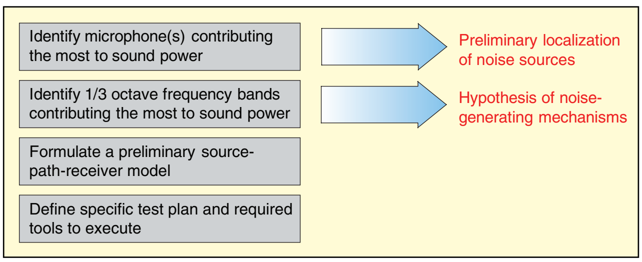

Figure 4. Sound power data to test plan process.

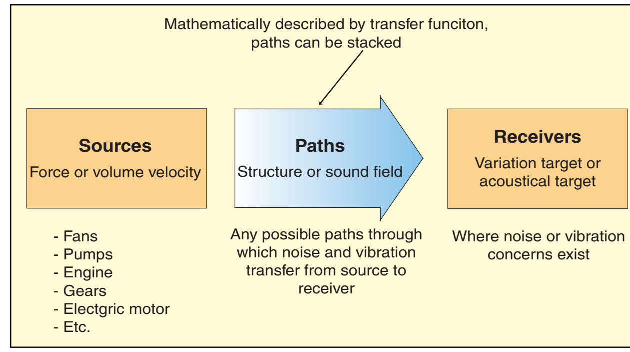

Figure 5. Source-path-receiver model.

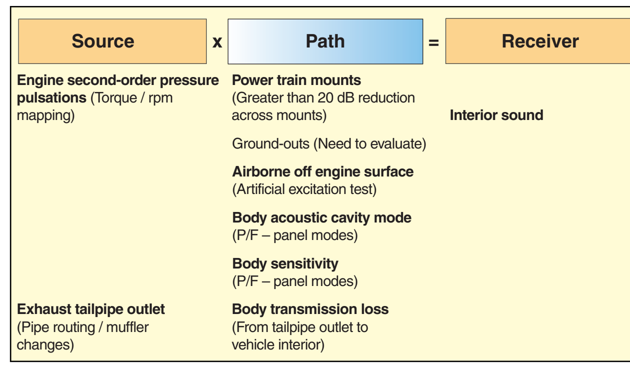

Figure 6. Source-path-receiver model for engine-related boom.

of the product and the systems can then be monitored throughout the development stages, and warning signals can be put in place to avoid costly late program changes. Once the system is put in place, the number of late program changes will be reduced and will then be attributed to lack of reaction to the warning signals.

The key information learned in the troubleshooting process that identifies the sources and paths is also the key to understand major contributors to the issue. This can be done through target cascading where system-level targets are backed up through the system to identify component-level targets and eventually to set component-level design specifications on those key contributors.

The approach to noise and vibration problem solving evolves as a company gains confidence in its NV capabilities. Figure 2 shows an example of the steps a company may take to evolve from a reactive response on NV issues toward a proactive position where they are designing products with the NV performance in mind and are able to predict problems and to resolve them before they occur. The ultimate goal often becomes the efficient design of low noise and vibration products.

Identify Problem

A common situation involves troubleshooting results from a product not complying with a specification. This can be a specification to limit and regulate exposure to noise/vibration in the workplace or in the community (OSHA, ISO, etc.). In the case of consumer products, etc., the specification might be sound power (noise), or vibration level at mount locations.[1] For vehicles, it might be sound power (agricultural/off highway/construction), or pass-by noise requirements (passenger/commercial vehicles).

An example of this type of specification is a sound power requirement for a consumer product. Although the target level varies, this is one of the most common types of standardized tests. An example of such a test is shown in Figure 3.

The sound power spectrum is generated using constant percentage bandwidth (CPB) analysis, most often in one-third-octave bands. CPB efficiently summarizes the information contained in a frequency spectrum; therefore it facilitates A-to-B comparisons between products/configurations. This information can guide development of a problem-solving work plan. The information and direction is limited by the data processing, and troubleshooting work must be done using narrow-band frequency analysis. The process to go from a sound power test to developing a specific test plan is shown in Figure 4.

The other category for noise and vibration concerns is when there is a problem with the product image related to sound and/or vibration quality (SVQ).[2] This can occur when the product is perceived as worse than competition, the product complies with regulations but has poor sound/vibration quality (customer complaints, warranty claims) or when the product by itself is good but creates poor SVQ when installed in the final application.

The first step in troubleshooting a SVQ issue involves getting agreement with the customer of the issue at hand. If an SVQ target is not in place, then this has to be defined and agreed upon before starting the troubleshooting investigation. This target must be as specific as possible and is rarely an overall level during standard operation. The target should be particular to the issue at hand and might be a specific order, frequency band, variation versus time, etc.

Smart Testing to Understand Your Product

Source-Path-Receiver Model. The most straightforward method to address a noise and vibration concern is to break it into separate parts using the source-path-receiver model shown in Figure 5. What the customer complains about, what we set targets for and what we initially measure to represent the noise or vibration concern is the receiver position. This measurement is the most appropriate for representing the voice of the customer but is generally not enough to provide good engineering insight to all of the design opportunities available to address the issue.

To understand the options available to resolve the issue, the sources and paths should be identified and then quantified. Breaking the problem into these categories leads to the development of a test work plan and allows for a better understanding of the issue.

For example, a vehicle boom issue was measured in the vehicle interior and was determined to be related to second-order engine firing. This was done by measuring engine speed during the objectionable noise condition and determining that the frequency of the noise concern was equal to twice the RPM of the engine. The first decision in the source-path-receiver model is what to bound as the source and whether to treat it as a black box or to break it down even further. This decision depends on your engineering responsibility in the program.

If you are a vehicle-level engineer and your responsibility is full-vehicle NV performance, then the engine can be considered a black box source that produces second-order pulsations that are input to the exhaust. It may be that the energy from the source needs to be reduced, but someone else is responsible for that, and you are just considering it a black box. On the other hand, if you are the engine manufacturer, then the engine itself needs to be broken into a source-path-receiver model to reduce the amount of energy it produces. The source would be the engine combustion, the paths would be the engine design and structure, and the receiver would be the engine second-order pulsations output to the exhaust. An example of the source-path-receiver model for a vehicle-level engineer working on an engine-related boom issue is shown in Figure 6.

Operating Tests and Artificial Excitation Tests. Understanding the noise and vibration performance of your product often requires measuring more than just sound pressure and vibration. Measuring other physical parameters that affect the operation of the system or define a repeatable test are often required:

- Temperature
- Pressure
- Forces/strain
- Flow rate
- Speed/RPM
- Linear/angular velocity
- And others

It is important to understand if the issue is caused by forced response or by a system resonance. This is because the countermeasures and design fixes are different for each. To do this, it is necessary to change the operation of the system from its nominal settings and perform sweep testing and artificial testing.

Using the engine-related boom issue from before as an example illustrates the necessity of using these two basic techniques. The issue may be due to forced response, which would say that system energy is transferred to the receiver and is too high. Reduction of the source is one option, along with barriers and breaking paths so the energy cannot flow to the receiver. However, if the issue is due to one of the paths going into resonance and amplifying the energy in the system, then the fix can still be reducing the source but can also involve changes to stiffness and mass to shift the resonance out of the operating range. Also, damping can be increased to limit the response of the resonance.

A sweep test can assist in understanding the situation through a visual interrogation of the data. Measurements are made at likely path points between the source and receiver while the source is swept through a speed range. Data are then plotted in 3D format with frequency and rotational speed as the x and y axes as shown in Figure 7. When plotting the data in this format, the sources are speed varying and seen as a diagonal. A resonance in the system is not speed varying and is shown as a vertical line.

The speed sweep described will have variances based on the type of system being tested. For a vehicle, the sweep might be an engine sweep or a vehicle speed sweep, where in a DC motor, it would be a voltage sweep, and an AC motor would be a line-frequency sweep.

Another technique used to understand the system is artificial excitation testing. This is sometimes done as an alternative to sweep testing if the system doesn't allow for a source sweep. Generally this is done in conjunction with sweep testing to further investigate areas to focus on design improvements. The most common method for artificial excitation testing is with an impact hammer and a roving accelerometer to measure various frequency response functions (FRFs) of the system. For example, rotating parts such as a fan blade cannot be easily measured during an operating test without a non-contact transducer. A measurement along the path, at the housing for example, may have shown a resonance in the system. Artificial testing of the rotor, hub, fan blade, and housing can then be performed to determine which of the individual components in the structure is contributing to the overall response.

Artificial excitation testing is also a quick and easy way to find out which resonant frequencies radiate more noise. In Figure 8, sound pressure due to force input is measured by impacting the system with a hammer at one location and measuring the resulting sound pressure at the receiver location.

A shaker or impact hammer is used to measure the system sensitivity to structural excitation. To measure the system sensitivity to acoustic excitation, a calibrated loudspeaker is used as the source. The data from these tests should be analyzed with a narrowband FFT analyzer with high enough frequency resolution to identify closely spaced resonant frequencies from different elements in the system.

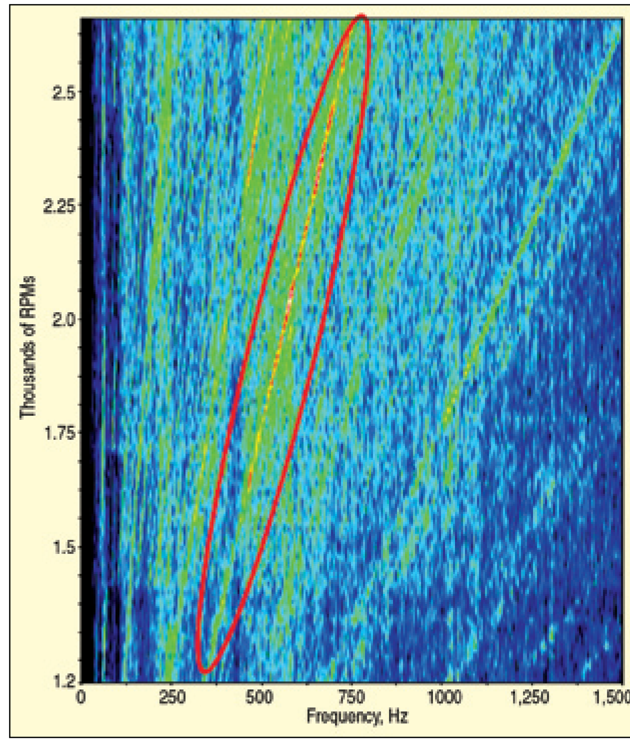

Figure 7. Color map of engine sweep data

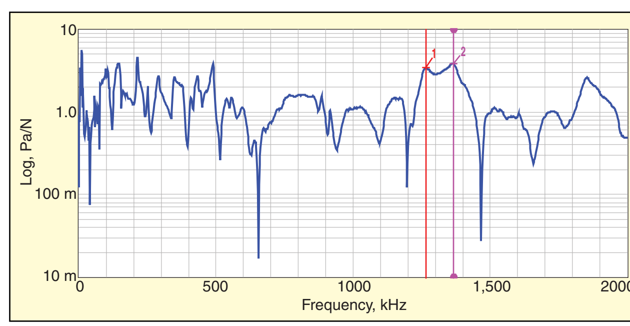

Figure 8. Sound pressure/unit force (P/F) data example.

Problem-Solving NV Tools

Order Tracking. Order tracking is an important troubleshooting tool to use for identifying the source and characterizing the paths as well as for better description of the receiver.[3] For a specific noise issue, it is very important to set an acceptable level particular to the issue you are concerned with, and order tracking is a method to support rotating machinery components. For example, if you have an engine boom issue as described earlier, the critical measurement to evaluate is the second-order engine order. If you have a gear noise issue, you are only concerned with gear-mesh-related orders and so on.

Order analysis is often plotted against speed or time and is the diagonal line extracted from the color map shown in the sweep data. For the graph shown in Figure 9, the data are shown for a before-and-after run and plotted against rotation speed.

Structural Techniques. To understand the structure enough to make a design modification, it is often necessary to define the motion of the structure during an objectionable event. The two methods used to describe these motions are operating deflection shapes (ODS) and experimental modal analysis (EMA).[4,5] ODS can be performed as time, frequency spectra, or be RPM based. EMA is performed with hammer or shaker input.

The goal of ODS is to determine the real-world forced deflection during operation through measuring transmissibility between a reference transducer and a group of roving response transducers. The goal of modal analysis is the construction of a mathematical

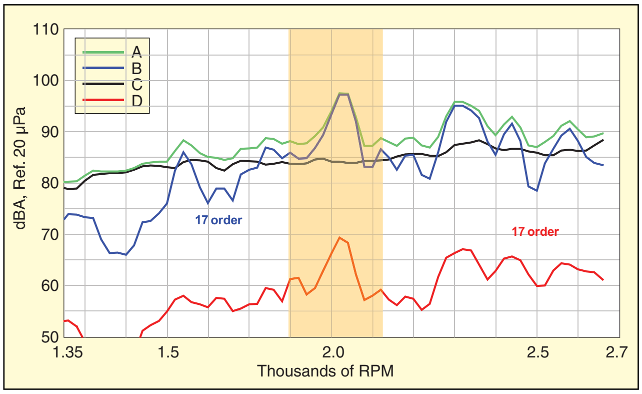

Figure 9. Engine second-order data example: (A) rear mic, overall, baseline; (B) rear mic, 17th order, baseline; (C) rear mic, overall, modified; (D) rear mic, 17th order, modified.

Operating Deflection Shapes (ODS)	Experimental Modal Analysis (EMA)
Can be defined *at any moment in time or frequency*	Modes are defined at *specific frequency*
Can be used on *nonstationary and nonlinear devices*	Test can only be done on *stationary, linear devices*
Can help *identify forced vibration*	Only shows *resonant vibration modes do not change* unless material of boundary conditions change
Deflections will change if material, boundary or load changes	Does not depend on external forces (modes are inherent to structure)
Dependent on loads placed on structures	Does not have units and *only shows resonances* compared with one another
Has units and shows *real vibration*	

Figure 10. Comparison between ODS and EMA.

model of the inherent dynamic properties and behavior of the structure through measuring the frequency response function between a force transducer at a driving point and group of roving response transducers. The differences in the two techniques are shown in Figure 10.

Noise Source Identification. There are a variety of noise source identification techniques available today including sound intensity, acoustic beam-forming and acoustic holography.[6] These techniques are used for a number of reasons outside of troubleshooting including calculating sound power, deriving acoustic impedance, estimating sound radiation and calculating surface velocities for acoustic modeling support. For a troubleshooter, however, the primary purpose of noise source identification is to identify the location where the majority of the noise comes from.

This is of particular interest in a complex acoustic environment, where localization of the source can be difficult such as the interior of a vehicle or in an engine compartment as shown in Figure 11. Identifying the location of the source with these techniques is also useful in small electromechanical devices that operate with a cover and the source is difficult to separate. Batteries for hybrid vehicles with integrated pumps and cooling fans, medical devices, document sorters, and small gear trains are examples of products where localizing the noise source would be very difficult without these techniques.

The decision on which noise source identification technique to use for troubleshooting purposes is based on factors such as frequency range of interest, size of test article, time available to test, measurement distance, resolution required, and whether the test can be run in a stationary condition.

Source-Path-Contribution (SPC). SPC is also known as transfer path analysis (TPA) and noise path analysis (NPA).[7] It uses the source-path-receiver model and better detailing of the paths to build a mathematical model representing the vibration or acoustic response of the system. There are several details in executing an SPC model, and each of the major software vendors has a product and training classes in the process.

The SPC method identifies the amount of excitation (source)

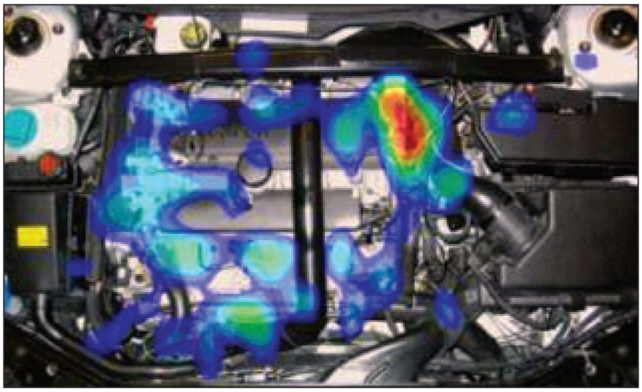

Figure 11. Noise source identification color map.

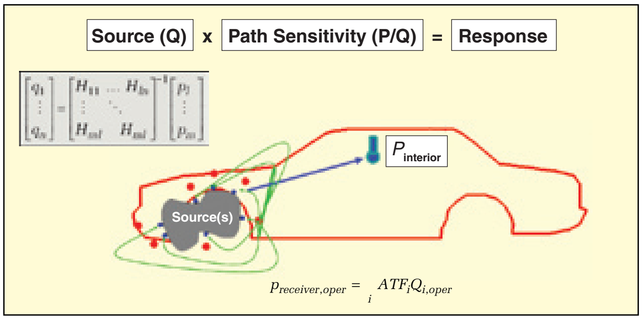

Figure 12. Airborne SPC example.

going into a particular path and combines that with the sensitivity of that path to calculate a partial noise and/or vibration calculation. This process is done for each path in each direction, and the result of all these partial contributions can be summed to calculate the total response. The process can be performed for structure-borne or airborne paths, and a diagram of the data flow is shown in Figure 12.

For a troubleshooter, the completion of a detailed SPC model may be out of reach from a resource or timing perspective. However, the SPC method does provide a logical process that tracks the excitation energy through the system and determines the contribution of each path to the overall noise or vibration concern. A troubleshooter normally also relies on some engineering judgment along the way to greatly streamline the process, and the focus is more on quantifying some key paths and looking for resonances through quick-impact testing of driving-point response and acoustic sensitivity.

The SPC model is an excellent tool for a complete understanding of the system. It gives an organized format to view the importance of each path and allows an engineer to make analytical changes to sources and sensitivities and predict overall response without making hardware changes. It is also very useful for developing targets at both the overall and subsystem level and can be leveraged to improve most product development processes for improved noise and vibration performance.

Countermeasures and Mockup/Changes to System. Another set of tools that are often overlooked by noise and vibration test engineers is the use of countermeasures and hardware changes to get a directional understanding of what changes affect system performance. Mock-up changes are generally used to determine if the noise is airborne or structure borne or to block some key paths to get an estimation of their contribution to the overall response. By mocking up countermeasures, one tries to highlight some areas as opportunities and cross other areas off the list. Using the engine boom example again, we can determine if the noise is coming from the tailpipe by piping the exhaust away and see of the noise has diminished dramatically. If the overall response remains unchanged, then you would say that airborne noise from the tailpipe is off the list of control possibilities. If the overall response drops significantly, then the transfer function between the tailpipe and the interior might be a key factor in reducing the noise.

A few examples of changes for acoustic and structural concerns are shown below:

- Acoustical
  - Acoustical wrapping: source of noise completely wrapped with barrier material and noise measurements made in this configuration and with barrier material removed in stages.
  - Sound absorption (foam) inside cavities or alongside surfaces/walls
  - Barrier (heavy material) to block one or more paths
  - Intake and exhaust of motors/generators connected to large absorptive mufflers to remove tailpipe/snorkel noise
- Structural
  - Mechanical disconnect
  - Replace mounts with softer material
  - Add mass or supports to change damping or stiffness

Predicting NV Performance

As noted earlier, the ultimate goal for a company, in improving the noise and vibration of their product, often becomes the efficient design of low noise and vibration products rather than the efficient troubleshooting of the noise and vibration issue. To improve the design of a product specifically for noise and vibration requires a full understanding of the system and the level of understanding that can be gained through test data.

Test-based predictive models involve two major steps, decomposition and synthesis, and they are both based on the source-path-receiver model.

- Decomposition (from full system to sources/paths)
  - The product is ideally decomposed in sources and paths
  - Sources are characterized by their operating level, and paths are characterized by transfer functions measured by artificial excitation testing
  - Once individual contributions are estimated, then the effect of design changes on each contribution can be predicted
- Synthesis (from component to full system)
  - Data from component test data are used to predict (by synthesis) the contribution of the component in the final system
  - Boundary conditions are added as transfer functions such as: predicting in-vehicle tire noise from a single tire-on-roll test in the lab;[8] and predicting change of pass-by noise for a given vehicle due to a change of one or more of the vehicle sources (engine, tires, exhaust, intake)

Test-based predictive models are the natural precursor of simulation-based models, which can be exercised to make design decisions early in the development cycle. Simulation-based models however need to be validated on existing hardware to ensure that they truly represent the relevant physics of the system. An intermediate step in the progression between test and simulation models is represented by hybrid models, where test data are typically used to represent systems too complex to model.

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