

A Unique Software Tool for Automotive NVH Troubleshooting

Giovanni Rinaldi, Chris Moon and Bret Engels, Brüel & Kjær, Canton, Michigan

A unique MATLAB-based, coded, engineering software tool (Time-Frequency Analyzer Core[®]) was developed that allows users to process acquired time data to help in identifying sources and paths of noise and vibration. The Time-Frequency Analyzer Core (TFAC) software does not replace commercial off-the-shelf software/hardware NV-specific tools such as modal analysis, ODS, acoustic mapping, order tracking, etc. Rather, it aims to provide basic, yet powerful data inspection and comparison techniques in a single software tool that facilitates drawing conclusions and identifying the most effective next steps. The features and advantages of using this software tool will be explained, along with a description of its application to a few different case histories (automotive and off highway/agricultural).

This article describes a MATLAB-based tool that incorporates the common strategies involved in addressing a system/subsystem-level noise and vibration concern. The tool was developed within the scope of a Small Business Innovation Research Phase 2 Program for the U.S. Air Force.

The objective was to deliver a software tool to aid troubleshooting laser beam jitter induced by optics and platform vibration. This tool was developed to include the most effective signal inspection and processing techniques for understanding the nature of the problem and for guiding control and system engineers toward possible fixes.

High-energy laser systems are installed in many different applications for a variety of military and commercial uses with extremely tight beam quality requirements. In the directed-energy community, proprietary and classified codes to debug subsystems and components are developed in MATLAB, and noise/vibration commercial-off-the-shelf tools are not in widespread use. Software control engineers, line-of-sight (LOS) specialists and system integration experts in the directed-energy community lack specific noise and vibration knowledge yet often find themselves dealing with beam quality not meeting requirements due to excessive vibration of the platform to which the optics are mounted.

Specifications and validation data are typically analyzed in terms of simple or multiple coherence functions in the frequency domain, with little or no investigation of temporal characteristics. One of the objectives of the software tool described here was to provide the non-NV engineer with a minimally redundant set of signal processing tools in both frequency and time domain to aid in understanding the problem.

In addition, because Time Frequency Analyzer Core, or TFAC, is coded in the MATLAB environment, it interfaces painlessly with proprietary MATLAB routines for which it provides an easy and simple data displaying and plotting capability.

Finally, TFAC does not compare to or compete with NV commercial off-the-shelf software, since it includes only a limited number of signal processing techniques used routinely by the authors as a starting point in any NV troubleshooting activity. The typical NV troubleshooting approach that is integrated into TFAC is described below along with a description of its application to a couple of different cases (automotive – door sound quality, and off highway/agricultural – SPC model development).

Typical Troubleshooting Approach

Noise and vibration issues can generally be separated into two categories:

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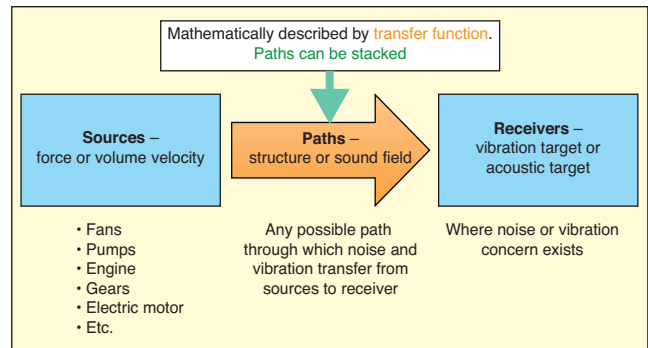


Figure 1. Source-path-receiver model.

- A problem caused by lack of compliance to a regulation or specification.
- Product does not perform adequately in-situ, causing sound and/or vibration quality (SVQ) concerns.

A product that does not meet the requirements of a regulation/specification is obviously a first priority, whereas a SVQ concern typically relates to a product that is perceived as worse than the competition, or when the product complies with regulations but has poor sound/vibration quality (customer complaints, warranty claims) or even when the product by itself is good but creates poor SVQ when installed in the final application.

Once the problem has been identified, the most straightforward method to address a noise and vibration concern is to break it down into separate parts using the source-path-receiver model as shown in Figure 1.¹

The receiver is where the noise or vibration concern exists, and it may be what the customer complains about or where targets are set. This is typically where measurements are made to represent the noise or vibration concern. Although this measurement is the most appropriate for representing the voice of the customer, it is not enough to provide insight into the noise/vibration-controlling mechanisms. To do that, sources and paths need to be understood. Sources are the “prime movers,” – engine, electrical motors, compressors/pumps, fans, gears, etc. that inject mechanical or fluid forces or acoustic source strength into the system. Paths are the interface between each source and the receiver and represent the system sensitivities to the forcing functions (structural, fluid, or acoustic).

Decomposing the system in a systematic way into sources and paths leads to developing a test work plan and allows for a better understanding of the issue. As it is well known to NV engineers that to understand whether the issue is related to either a source or a path, it is important to understand if the issue is caused by a forced response or by a system resonance. To do this, it is necessary to change the operation of the system from its nominal settings and perform sweep testing and artificial testing. A sweep test that allows for variation of operating condition (speed, load) can assist in differentiating between a forced response and system resonances. Artificial excitation tests are used to measure the system sensitivity to structural or acoustic excitation.

Once forced response and resonances are understood, additional specialized NV tools are needed to continue the troubleshooting, such as order tracking, modal analysis, operating deflection shapes (ODS), noise-mapping techniques like sound intensity, near-field acoustic holographic and beamforming, source-path-contribution (SPC), also called transfer path analysis (TPA), and several others.

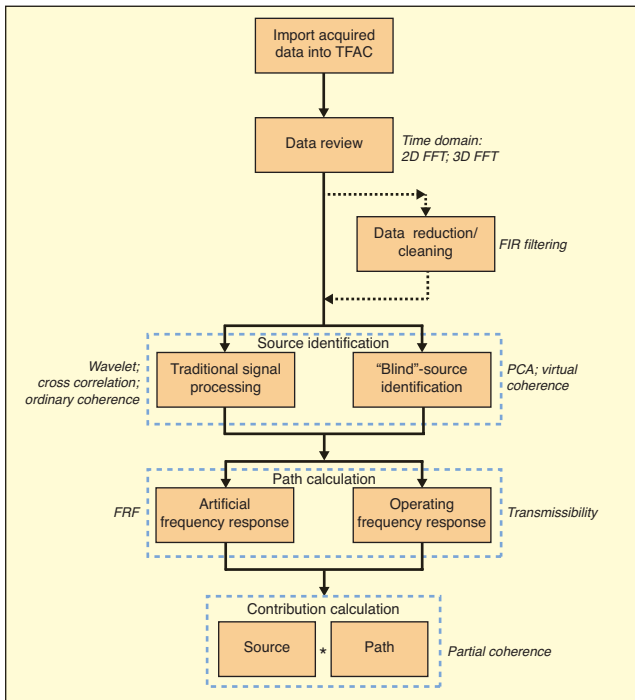


Figure 2. TFAC workflow chart.

TFAC software helps engineers in the first phase of troubleshooting toward formulating hypotheses of root-causes and deciding what are the most effective next steps toward solving the problem.

TFAC Software Description

The TFAC interface is based upon the .NET application framework and employs MATLAB for performing signal processing routines. The use of .NET framework enables a high level of compatibility and integration with the Windows environment and external applications and a high degree of customizability. As indicated by the C in its name, TFAC is a "core" NV analysis product; all base functionality that an NV engineer would expect is included. However, additional analysis modules may be added to encompass specific needs. TFAC is strictly a processing/postprocessing tool and does not control acquisition, but instead imports data.

The supported file formats for import are:

- Universal files data-set 58 (*.uff) – both ascii and binary
- MATLAB (*.mat)
- Labview (*.lvm and *.tdms)
- B&K Pulse (*.pti and *.bkc)

TFAC provides a workflow that features the following:

- Data inspection of time domain and processing of both spectra plots as well as time-frequency plots (autospectra and spectrograms).
- The candidate source signals can also be inspected in time-frequency format using a wavelet presentation that is used to provide a better trade-off between spatial and frequency resolution.
- Ordinary coherence functions can be presented between defined input/output signals and input/input signals.
- A statistical procedure used for finding patterns in the data of high dimension called principal component analysis (PCA) can be used to identify the number of significant sources in a linear system/subsystem. These decomposed sources can also be used to present virtual coherence functions between each source of significant variance found in the signals compared to the original, nondecomposed signals.
- Cross-correlations can be performed across candidate sources and paths signals to identify temporal causality.
- Digital filtering – low-pass, high-pass, band-pass, and band-stop (notch) FIR (finite-impulse response) filters can be applied to signals implemented for signal cleaning/preprocessing purposes.
- Operating transmissibility and frequency response function (FRF) from artificial excitation tests can be inspected as well for single-input, multiple-output inspections.

- Partial coherence can also be applied on a reduced set of potential inputs to evaluate uncorrelated contributions to the input along with calculating the percent contribution to the input.

TFAC is laid out to guide the user toward first inspecting the signals in time domain to make judgments about signal quality to identify any valuable signal characteristics and then also select possible regions of interest for processing. It is assumed that the user may first want to make some inspections on individual signals with 2D spectra or 3D Fourier or wavelet spectrograms.² At that point it may be useful to perform batch processing of the signals using any or all of the above mentioned methods depending on the goals. This workflow is shown in Figure 2.

There are numerous software packages that give a user the capability to perform the so-called source-path-contribution (or transfer path analysis) methods for many different structures in terms of structure-borne and/or airborne contributions. Often though, these software packages don't allow the user access to some of the underlying individual steps that go into the signal decomposition process. Having access to a singular-values plot as well as ordinary, virtual and partial-coherence functions may aid the user in troubleshooting a system or as a pre-test development phase for a more complicated source-path-contribution test.

Application 1 – Automotive Door Sound Quality

Door closure sound quality is a major concern for automobile manufacturers due to it being one of the first sounds heard by a customer visiting a dealership.³ It strongly affects the expected image of that vehicle in the customer's mind. Vehicle manufacturers have placed a strong emphasis on understanding and designing door closure sound quality. In support of an on-going development effort put forth by an automotive original equipment manufacturer (OEM) for door closure sound, a characterization of the acoustic performance of multiple vehicles was performed to understand their differences, since it relates to perceived sound quality.

Since it is well known in the NV community,⁴ wavelet transforms are useful tools for resolving low-frequency content in door closure sounds. Vehicle door closure events may contain low-frequency door structural resonance characteristics combined with higher frequency rattle events. This balance between low- and high-frequency content as a function of time is better understood by inspecting a wavelet spectrogram (Figure 3), where Figure 3a shows a Fourier spectrogram and Figure 3b shows a Morlet wavelet spectrogram for the same vehicle closing event. Clearly, the wavelet spectrogram provides superior time/frequency resolution.

Classic time domain cross-correlation approaches can also be useful in some cases to aid in causality and correlation investigations.⁵ Since a door closure is a transient event, a time domain cross-correlation can sometimes be more attractive than looking at frequency response and phase relationships.

Figure 4a shows five signals from a larger acquisition, where the problematic transient issue was evident. Visual correlation and causality may be possible with just several plots like these, but when many signals and events are analyzed, then a cross-correlation implementation can become more useful, as seen in Figure 4b.

The peak lead or lag times from a cross-correlation calculation provide bi-variate causality for inspection, and then a correlation coefficient calculation provides a measure of correlation, again in a bi-variate sense. (Simply put, the cross-correlation indicates which transient occurs first and this is assumed to be the source.) Oftentimes, the process is aided with some level of signal processing/filtering (like high, low or band-pass) along with selecting or focusing on shorter time segments of the signal. As seen in Figure 5, a low-pass FIR filter was performed to remove any higher frequency content that is not relevant to understanding the transient event.

The correlation matrix shown in Figure 4b gives an example of the same five signals (from Figure 4a) with the resulting lead/lag values and their corresponding correlation coefficients. The lead-to-lag assessment here shows that signal (Channel 1) leads the rest of the signals (Channels 2, 7, and 8). The signal (Channel 2) also shows a relatively strong correlation coefficient (0.7526) when compared to another signal (Channel 7). Judgments regarding the lead/lag times can be left for the pairs with a significant correlation

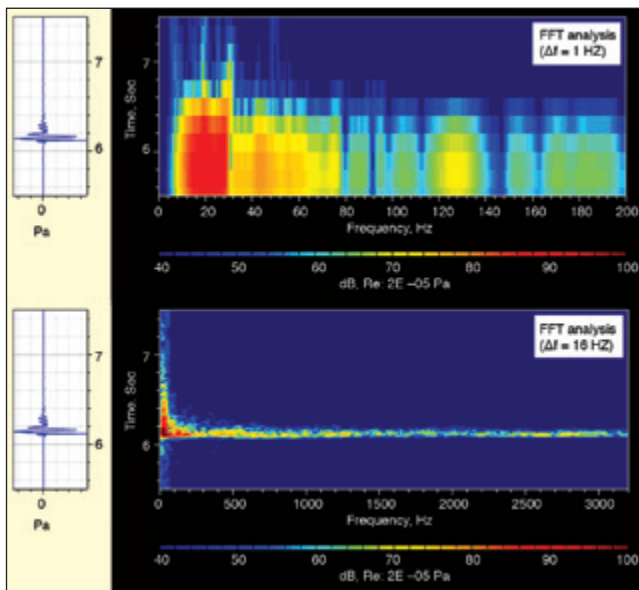


Figure 3a. FFT with ($\Delta f = 16$ Hz, 90% overlap) domain presentations of interior microphone response for car door closing; zoomed/low-frequency range (top) and higher-frequency range (bottom).

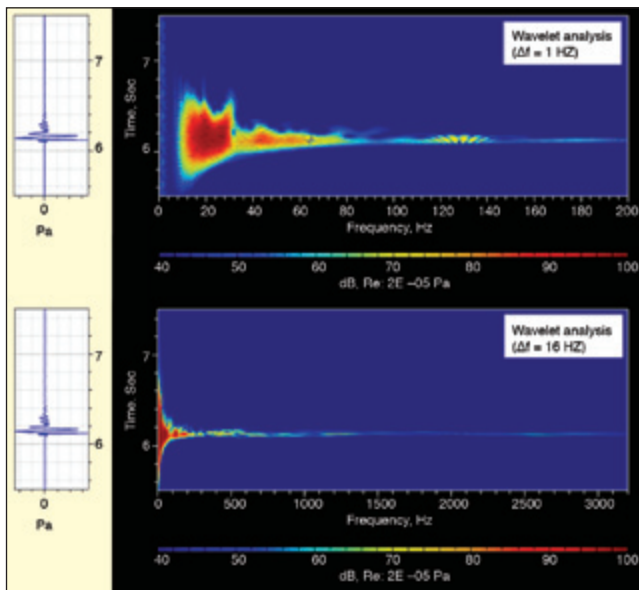


Figure 3b. Morlet wavelet domain presentations of the interior microphone response for car door closing; zoomed/low-frequency range (top) and higher-frequency range (bottom).

coefficient. Also, additional judgments regarding lead/lag times should take into consideration structural junction impedances in the system, airborne impedances or distance delays, as well as any acquisition phase delays.

Application 2 – Off Highway SPC Model Development

For this next application, experimental data were used to validate a computer-aided engineering (CAE) model that predicts acoustic performance for a truck cabin of a commercial vehicle manufacturer. The CAE model developed was to be used for the design and optimization of sound packaging of future vehicle models.

During the experimental phase of this project, an SPC (source-path-contribution, also known as noise/transfer path analysis) model was developed on the existing vehicle and updated with individual components from test and CAE for future vehicles. Once the SPC model was established, then the individual contributions from each of the structural and acoustic sources can be interrogated further to identify which components or systems are the primary contributors to any undesired sounds. Therefore, a substitution of alternate design iterations can also be evaluated within the SPC model to validate proposed design changes.

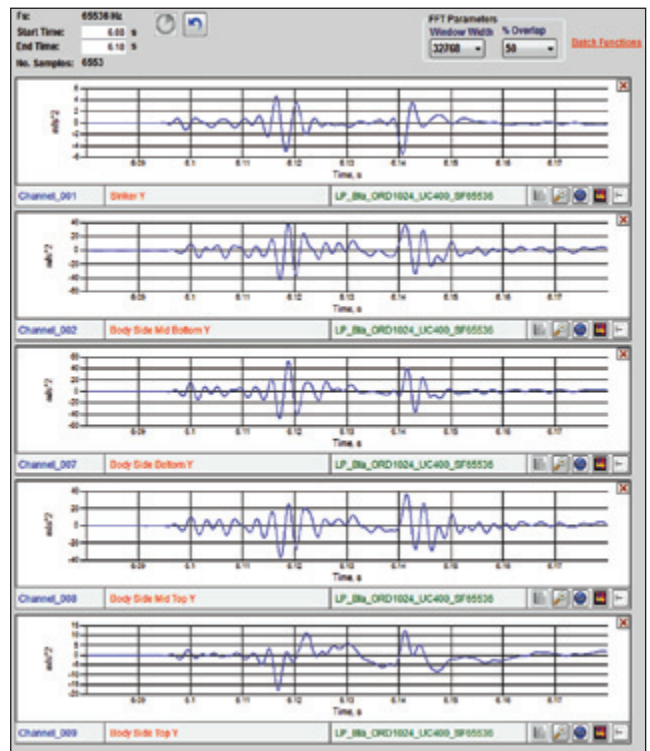


Figure 4a. Door closing event system examples highlighting problematic transient events to be used for a cross-correlation analysis.

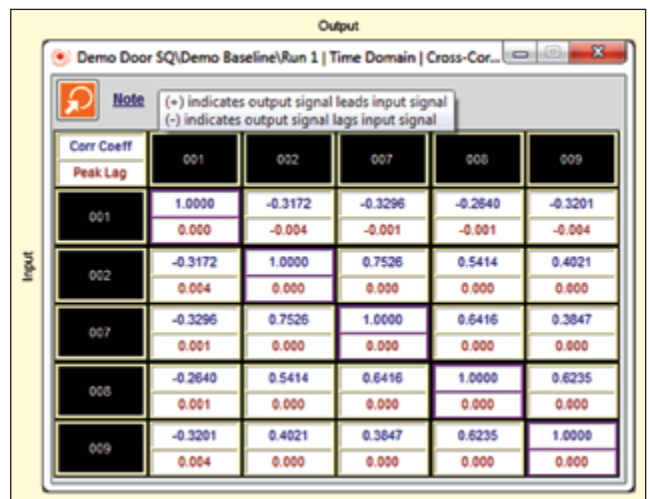


Figure 4b. Bi-variate cross-correlation lead/lag times and correlation coefficient values for an inspection of five signals.

For the SPC testing of the commercial vehicle, acoustic sources such as engine, transmission, cooling fans, etc., were mapped with microphones. The points-of-force injection into the cab are the cab mounts, which were instrumented with accelerometers. In a first-level SPC approach, the noise at the operator's ears is decomposed into airborne contributions from each and all acoustic sources and structure-borne contributions from each and all cab mounts.

In addition, we wanted to understand the airborne contribution from the exterior sources through each cab surface (front, rear, sides, floor and roof), so multiple microphones were placed all around the cab surfaces to measure the acoustic loads into the cab. In this case, a typical problem encountered is determining how many of these near-field microphones are needed for an accurate estimation of the acoustic load. In other words, how many sources hitting the cab surfaces need to be represented in the SPC model. An objective approach to understanding the number of sources needed within a SPC model is to utilize principal component analysis (PCA), and TFAC was used for the PCA processing.

Figure 6 shows the singular values from TFAC for a set of microphones defined as inputs to the vehicle interior system during



Figure 5. Time-domain presentations of original response (top) along with the corresponding low-pass filtered response (bottom) for car door closing.

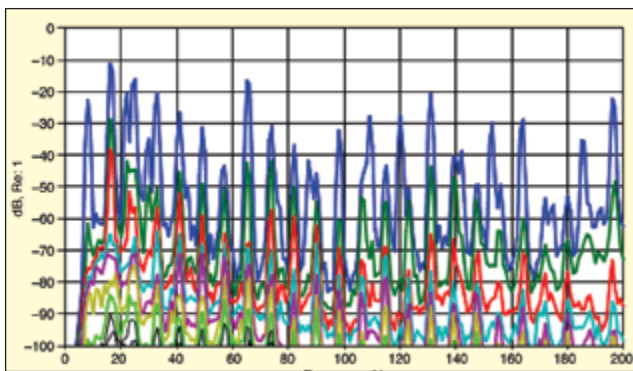


Figure 6. Singular values for set of vehicle microphone locations.

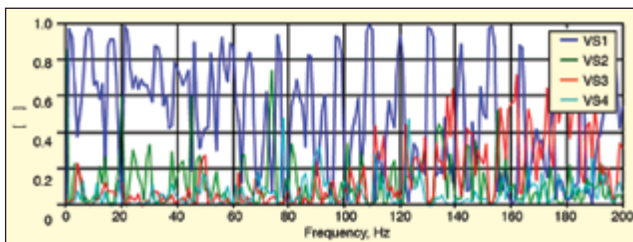


Figure 7. Virtual coherence between first four singular values and single microphone location.

steady-state operation of a commercial vehicle. At each spectral line, an assessment can be made regarding how many sources of significant variance likely exist in the selected data set for a linear system.

The virtual coherence from TFAC^{6,7} between each input signal and each singular value may also be inspected to assess the importance of the significant variance in each of the input signals. At this point the virtual coherence between the singular values and any signals defined as system outputs or receivers can also be inspected to study the input-to-output relationship (see Figure 7).


This approach may be suitable for making judgments about the number and possibly the location of sources. If possible, it may be used with classic source-on, source-off tests with the system under test. Though it is often the case where components may not be operated in isolation, leaving signal decomposition approaches to provide insight into the location of different sources in output or receiver signals. Additionally, these methods facilitated by TFAC can be used to refine a source-path-contribution test setup before further tests are continued.

Summary/Conclusions

A MATLAB/.NET software tool was developed that complements existing commercially available software packages. This tool, called Time Frequency Analyzer Core, or TFAC, includes several data display options, access to intermediate steps and data of classic signal processing algorithms and a combination of signal processing strategies to facilitate data interpretation and identification of a roadmap to solution.

As shown in Application 1, TFAC allows the user to make some inspections on individual signals with 2D spectra or 3D Fourier or wavelet spectrograms. This tool also allows for other traditional signal processing techniques, such as cross correlation and FIR filtering. Although not shown here, it is also possible and may be useful to perform batch processing of the signals using any or all of the above-mentioned methods, depending on the goals. TFAC allows access to singular value plots as well as ordinary, virtual and partial coherence functions here used as a pre-test development phase for a more complicated source-path-contribution test as explained in Application 2.

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The author can be reached at: giovanni.rinaldi@bksv.com.