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A Time and Frequency Tool for Noise and Vibration Troubleshooting

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ABSTRACT

Experienced Noise and Vibration engineers often utilize the same approach to diagnose root-causes of NV concerns. First, the system is inspected and potential sources and paths are identified. Next, noise and vibration data are acquired, typically with a COTS software/hardware NV solution, to map the behavior of the system under operating and artificial excitation conditions. Specialized NV software tools provide a great variety of data processing algorithms but the non-expert user may have a hard time in navigating through them all.

To address this need, a Matlab-based coded software (Time-Frequency Analyzer Core) was developed that allows to process acquired time data by means of the techniques that are most meaningful and effective toward identifying sources and paths of noise and vibration (in the experience of the authors). The Time-Frequency Analyzer Core (TFAC) software does not replace NV specific tools such as modal analysis, ODS, acoustic mapping, order tracking, etc., rather it aims at providing basic, yet powerful data inspection and comparison techniques that facilitate drawing conclusions and identifying most effective next steps.

1. INTRODUCTION

This paper describes a tool that incorporates the common strategies involved in addressing a system/subsystem-level noise and vibration concern. The tool was developed to allow users to identify noise and vibration related issues by aiding in the decomposition of sources and understanding the sensitivity of individual paths between sources and receiver positions. The features and advantages of using this software tool are explained, along with a description of its application to three different cases (aerospace, automotive, and off highway/agricultural).

2. TYPICAL TROUBLESHOOTING APPROACH

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 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. The receiver is where the noise or vibration concern exists, 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 generally not enough to provide good engineering insight into the noise/vibration controlling mechanisms that the troubleshooting activity is to address. To understand the options available to resolve the issue, sources and paths should first be identified and then quantified. Breaking the problem in a systematic way leads to the development of a test work plan and allows for a better understanding of the issue. First, to understand whether the issue is related to either a source or a path 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. Whereas 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 such as sound intensity; near-field acoustic holographic and beamforming; source-path-contribution (SPC); and several others. The Time Frequency Analyzer Core software described in this paper aims at helping engineers to understand the breakdown of the system into sources and paths and at facilitating the identification of the most effective specialized NV tool for the next step.

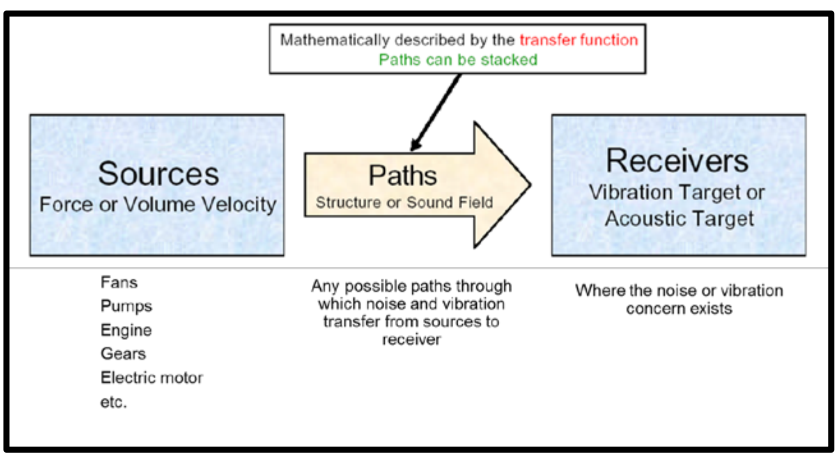


Figure 1: Source-Path-Receiver model

3. TFAC SOFTWARE DESCRIPTION

Time Frequency Analyzer Core (TFAC) is an engineering software processing tool (Matlab-based) that helps the user(s) to identify noise and vibration (NV) sources. Time based test data can be analyzed to determine the contribution of NV for different sources and paths. . The combination of editing and analysis tools also allows the user(s) to identify specific NV issues during specific time intervals.

The term "expert system" 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 described in this paper is a long way from fitting this definition, as it is a very simple and even crude way of replicating the thought process of an expert. However, this software does provide a thought process roadmap that guides the user(s) through several steps of data processing and that aims at facilitating the interpretation of the data.

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, as well as a high degree of customizability. As indicated by the 'C' in its name, TFAC is a "Core" NV analysis product; all of the base functionality that an NV engineer would expect is included, however additional analysis modules may be added to encompass specific needs.

TFAC provides a workflow that features the following:

1. Data inspection of time domain and processing of both spectra plots as well as time-frequency plots (auto spectra and spectrograms)
2. The candidate source signals can also be inspected in time-frequency format utilizing a wavelet presentation – which is used to provide a better trade-off between spatial and frequency resolution.
3. Ordinary coherence functions can be presented between defined input/output signals and input/input signals.
4. 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, non-decomposed signals.
5. Cross-correlation(s) can be performed across candidate source(s) and path(s) signals to identify temporal causality.
6. Operating transmissibility and frequency response function (FRF) from artificial excitation tests can be inspected as well for single input, multiple output inspections.
7. Partial coherence can also be applied on a reduced set of potential inputs to evaluate uncorrelated contributions to the input, as well as the calculation of the percent contribution to the input.

The TFAC layout gives the user the approach of seeing the signals first in the time domain to make judgments about signal quality, 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. 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.

There are numerous time-frequency software packages that give a user the capability to perform the so-called source-path-contribution 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 be sufficient to aid the user in troubleshooting a system or as a pre-test development phase for a more complicated source-path-contribution test.

4. APPLICATIONS

A. Aerospace

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 [1]. 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.

TFAC utilizes common signal processing algorithms to help the control and system engineers to quantify the jitter sources and paths in a consistent and accurate manner. In the application here described, 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 where servo-hydraulic-actuated), angular rate sensors measuring azimuth and elevation, control and Fine Tracking Error signals all being acquired simultaneously 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 (PCA) was used to identify the number of significant sources or signal variance in the system
- The low frequency content of candidate source channels was inspected by wavelet analysis
- Cross-correlation(s) was performed across candidate source and path “channels” to identify temporal causality when transient excitation events were present in the system.
- Conditioned Input Analysis using classic partial coherence methods was then applied on a reduced set of potential inputs to evaluate uncorrelated contributions to the receivers (Fine Tracking Errors, FTE)
- Operating transmissibility and FRF from artificial excitation tests were then inspected to confirm likely sources and their % contributions to FTE

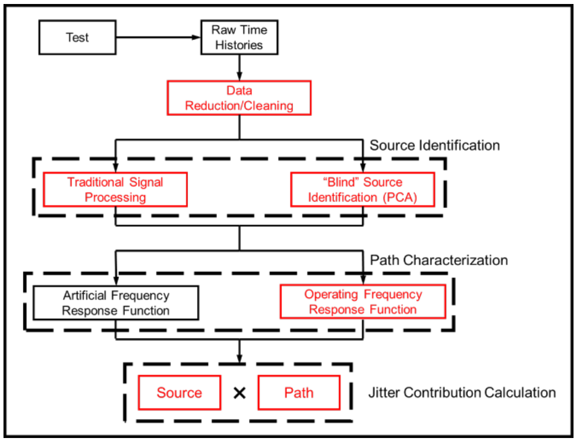


Figure 2: Jitter Vibration Decomposition process. Test task/data in black and analysis/software tasks in red.

The TFAC software was developed to mimic the steps summarized above 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 software could be useful in NV labs as a preliminary "data screening and interpretation" tool for less experienced engineers.

In the above example one stage of the process involved using classic partial coherence approaches to investigate contribution percentages from beam source elements on the end-result optical receiver. The linear effects of a signal is sequentially removed from other input and/or output signals. This process can be repeated until all of the signal power is removed. The conditioned spectra resulting from this decomposition can be inspected along with partial coherence functions. A contributions percentage due to the removal of each input signal can be shown which may highlight significant sources of correlated signal power in any output signals. Partially correlated references can make the ordering of the input power to be removed difficult, but partial coherence inspections can still be useful in some instances. Figure 3 shows a contribution percentage plot confirming a suspicion that a single source (signal #4 – Gxx04) was the dominant culprit in this optical system.

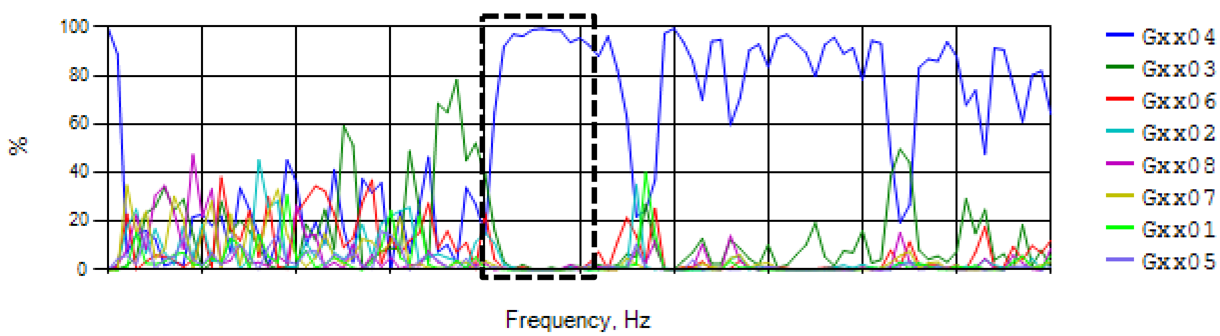
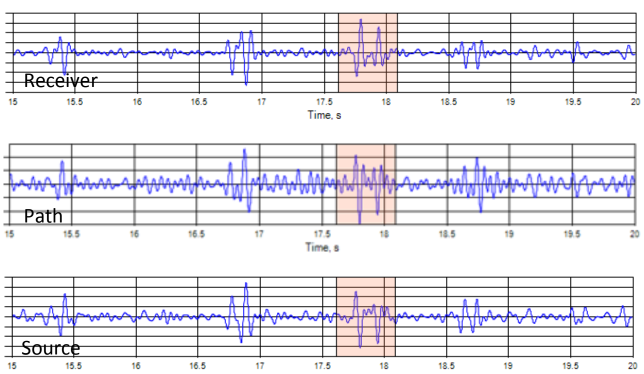


Figure 3: Partial coherence based contribution percentage results for a receiver signal in an optical system. Frequency region highlighted (---) is the analysis region of interest. Note that the frequencies are obscured in this example.

Classic time domain cross-correlation approaches can be useful in some cases to aid in causality and correlation investigations. If transient event problem solving is needed, then a time domain cross-correlation can be more attractive than looking at frequency response and phase relationships. Figure 4 shows three signals from a large acquisition where a problematic transient issue was evident in the end optical receiver. One transient event is highlighted in an intermediate path and also a suspect source location. Visual correlation and causality may be possible with just several plots like those in Figure 4, but when many signals and events are analyzed then a cross-correlation implementation can be helpful. The peak lead or lag times from a cross-correlation calculation provide bi-variate causality for inspection, and then a correlation coefficient [3] calculation provides a measure of correlation, again in a bi-variate sense. Often, the process is aided with some level of signal high, low or band-pass filtering along with selecting shorter time segments. The correlation matrix at right in Figure 4 gives an example of the three signals at left along with multiple signals and the resulting lag values and the correlation coefficients. The receiver at signal 6 shows a relatively high correlation coefficient to one of the path signals (#2) and also a system source signal (#7). Inverse correlation (negative value) can also be inspected with the sign of the correlation coefficient. Judgments regarding the lag times can be left for the pairs with a significant correlation coefficient. Additional judgments regarding lag times should take into consideration structural junction impedances in the system, airborne impedances or distance delays, as well as any acquisition phase delays.



Corr Coeff / Peak Lag	001	002	003	004	005	006	007	008
001	1.0000	-0.6612	0.4881	0.3806	-0.0891	0.4049	-0.8639	0.8372
	0.000	0.007	-0.006	-0.192	-0.110	0.014	0.003	-0.005
002	-0.6612	1.0000	0.0514	0.0121	-0.3521	-0.7227	0.8825	-0.4668
	-0.007	0.000	-0.017	-0.045	-0.118	0.007	-0.003	-0.011
003	0.4881	0.0514	1.0000	0.0609	-0.0299	-0.0938	-0.2245	0.5085
	0.006	0.017	0.000	-0.001	-0.078	0.023	0.013	0.003
004	0.3806	0.0121	0.0609	1.0000	0.2151	-0.0081	-0.1488	0.3522
	0.192	0.045	0.001	0.000	-0.077	0.052	0.193	0.188
005	-0.0891	-0.3521	-0.0299	0.2151	1.0000	0.3434	-0.1497	-0.1027
	0.110	0.118	0.078	0.077	0.000	0.127	0.116	0.108
006	0.4049	-0.7227	-0.0938	-0.0081	0.3434	1.0000	-0.6159	0.1072
	-0.014	-0.007	-0.023	-0.052	-0.127	0.000	-0.010	-0.019
007	-0.8639	0.8825	-0.2245	-0.1488	-0.1497	-0.6159	1.0000	-0.7948
	-0.003	0.003	-0.013	-0.193	-0.116	0.010	0.000	-0.008
008	0.8372	-0.4668	0.5085	0.3522	-0.1027	0.1072	-0.7948	1.0000
	0.005	0.011	-0.003	-0.188	-0.108	0.019	0.008	0.000

Figure 4: System input-to-output examples *(left)* highlighting problematic transient events to be used for a cross-correlation analysis. Bi-variate cross-correlation lag times and correlation coefficient values for an inspection of eight signals *(right)*

B. Automotive

Door closure sound quality is a major concern for automobile manufactures due to it being one of the first sounds heard by a customer visiting a dealership [2]. Since the door closure sound is one of the first sounds heard, it strongly affects the expected image of that vehicle in the customer's mind. Vehicle manufacturers have placed a strong emphasis on understanding of and designing for door closure sound quality. In support of an on-going development effort put forth by an automotive OEM for door closure sound, a characterization of the acoustic performance of two vehicles was performed to understand their differences as it relates to perceived sound quality.

Using a continuous wavelet transform presentation for door closing transient events can be attractive since showing a small Δf with a large time record (T) at lower frequencies on the same plot as a larger Δf with a small T at higher frequencies often aids in understanding the door closing event characteristics. Vehicle door closing events may contain low frequency booming, or door structural resonance characteristics combined with higher frequency rattle events. The wavelet scale presentation allows for this more completely within one plot, whereas the Fourier-based time-frequency presentation is constrained by one Δf, T relationship per analysis, even when aided by a large amount of overlap processing. Figure 4 shows a Fourier spectrogram and then also Morlet wavelet spectrogram for the same vehicle closing event. The wavelet presentation better defines the door's rattle temporal spacing above 2 kHz and then also some of the frequency characteristics below ~ 500 Hz. If the relationship or balance between low-to-high frequencies combined with the temporal characteristics need to be understood for these types of events, often a wavelet presentation is helpful.

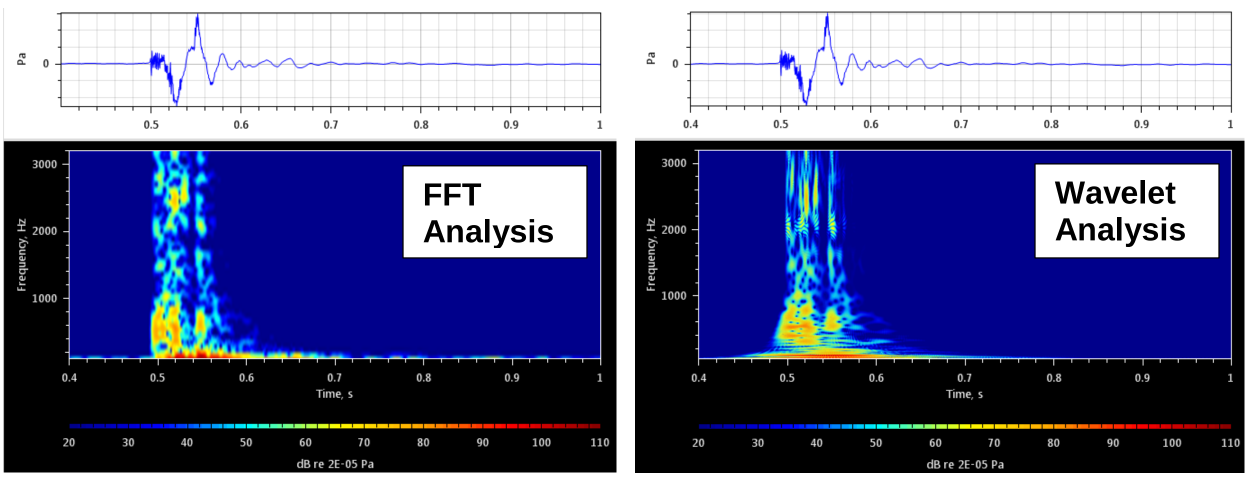


Figure 4: FFT *(left)* with (Δf = 64 Hz, 90% overlap) and Morlet wavelet *(right)* domain presentations of the interior microphone response for the same passenger vehicle door closing event.

C. Off Highway/Agricultural

Wherein this application, experimental data was used to validate a 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, a 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 vehicle(s). 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 prior to the availability of hardware.

A typical problem encountered when developing a SPC model is determining how many sources exist in the system being tested. Previous experience is often appropriate in designing a test, but often some initial inspection of data may allow for adjustments to a test setup. An objective approach to understanding the number of sources needed within a SPC model is to utilize Principal Component Analysis (PCA).

Figure 5 shows the singular values for a set of microphones defined as inputs to the vehicle interior system during 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 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 as shown in Figure 6.

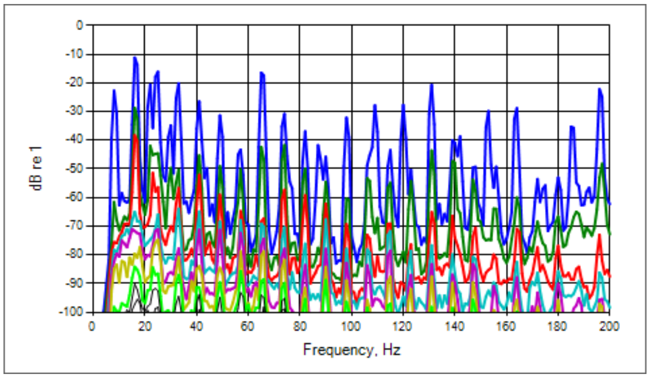


Figure 5: Singular values for a set of vehicle microphone locations.

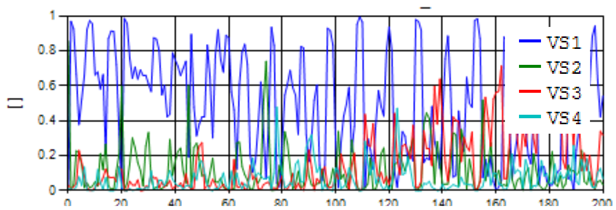


Figure 6: Virtual coherence between the first four singular values and a single microphone location.

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 can be used to refine a Source-Path-Contribution test setup before further tests are continued.

5. CONCLUSION

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.

6. REFERENCES

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