5th International Conference
″Computational Mechanics and Virtual Engineering ″
COMEC 2013
24- 25 October 2013, Braşov, Romania

MULTI-SPECTRAL ANALYSIS OF THE SELF GENERATED TORQUE'S SIGNAL WITHIN A 4X4 AUTOMOTIVE DRIVELINE

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Abstract: *This paper presents the way of achieving a data multi-spectral analysis and filtering. The specific data have been obtained by testing a 4x4 military vehicle's driveline while performing its motion with a tire radii difference between its axles. The mono-spectral analysis is a primary form of frequency analysis and it is described in first part of this article. It uses the amplitude and power spectra. The multi-spectral analysis is able to make the difference between the linear and non-linear components. It is quite useful since the systems are non-linear, time dependant. After multi-spectral analysis we do the data filtering. Finally, we decided that the most suitable filter would a 3rd order Savitzky-Golay filter.*

Keywords: *multi-spectral analysis, filter, driveline*

1. INTRODUCTION

The transmission (also known as the *powertrain* or *the drivetrain* or *the driveline*) is one of the most important systems of any automotive. The transmission is of a capital importance, since it is responsible for transmitting and modulating the intrinsic parameters of the power-flow from the engine to the driving wheels [1].

The all-wheel driven transmission yet has a big problem: the self-generated torque that occurs inside the driveline. The only way to override the wind-up torque, occurred inside of a normal drivetrain, is to increase the power delivered by the engine. On the other hand, this power loss can't be used as a driving power for the automobile. Hence, it leads to extra fuel consumption, supplementary wear of the drivetrain's components and of the tires. Nevertheless, decreased maneuverability should be taken into account [2].

The self-generated torque generates the loop power-flow. Loop power-flow within an automobile's transmission is generally due to the different lengths of the trajectories the vehicle's wheels are covering. There are many reasons generating this situation, but the main ones can be listed as follows: unevenness of the tire radii; wheels' slip; vehicle's cornering; traveling on uneven tracks [1],[3].

This paper presents the way of achieving a data multi-spectral analysis and filtering. The specific data have been obtained by testing a 4x4 military vehicle's driveline while performing its motion with a tire radii difference between its axles. The multi-spectral analysis of the data is actually a component of the frequency analysis of a signal. Frequency analysis covers a wide range of applications within the domain of the achieved data processing [4], [5], [6]. As some practical examples, it can be used when making a decision to filter some noises while identifying the useful signal or determining the important frequencies of the studied phenomenon.

An important feature when studying the experimental data is to determine the frequencies that provide the most powerful dissipation of the signal. Hence, one should realize what would be the process that generates the specific frequencies: it is a useful process's or signal's component or it is a rather noisy one, which should be further filtered. Moreover, this kind of analysis is also useful to determine the resonance frequency of the system and avoiding the process developing in the correspondent area.

Frequency analysis assumes the use of the Direct Fourier Transform (mono-spectral analysis) to studying the linear systems. Specifically, it assumes that the experimental data serials are rather stationary (no time history of the frequency spectrum). On the other hand, real life processes are non-linear, non-stationary phenomena with their frequency spectra varying in time. Therefore, a mono-spectral analysis could lead to errors. Again, a more accurate analysis could be achieved by using the multi (bi-) spectral analysis (so called Two-Dimensional Fourier Transform).

2. MONO-SPECTRAL ANALYSIS

The mono-spectral analysis is a primary form of frequency analysis. It uses the amplitude and power spectra. The amplitude spectra are used to determine the various frequencies occurrence within different domains, while the power spectra determine the frequencies where the signal dissipates most of the power. Hence, the last ones are really important when analyzing the signal.

The amplitude spectrum is obtained by developing the signal's Fourier serials. As an outcome, we can plot the amplitude weights of the signal across the frequency range, which leads, at its turn, at determining the type and the intensity of the mechanical load of a given component [7].

The physical meaning of the spectral power density, its mathematical representation should be analyzed. Basically, it represents the area under the Fourier Transform's curve, in other words the average power of a signal within a certain frequency band. The average power of the signal provides information with respect to the energy dissipated within the given band of frequency. Fig. 1 depicts two useful pieces of information: the relative amplitude and the power spectrum of a self-generated torque signal. This kind of representation provides much more information than the time history of the same signal.

We have to mention again that the mono-spectral analysis is "linearizing" the system and it assumes that it has no time history. Moreover, the mono-spectral analysis can't separate de linear from the non-linear component.

3. MULTI-SPECTRAL ANALYSIS

This kind of analysis is able to make the difference between the linear and non-linear components. It is quite useful since the systems are non-linear, time dependant. The multi-spectral analysis uses superior order, statistic moments. They are based on the generalization of the dynamic serials' self-correlation using the "cummulants", as they are nothing else but linear combinations of the above mentioned moments [8].

The first order cummulant is defined as the average of the signal as discreet time history and can be determined with (1), where $M\{\cdot\}$ will be considered to be the statistic averaging operator.

$$C_{1x} = M\{x[n]\} \tag{1}$$

The second order cummulant is defined as the self-correlation function that is used in the Fourier Transform analysis (mono-spectral analysis) and it computed using (2), where $x^*(n)$ is the reciprocal complex function of $x(n)$.

$$C_{2x}(k) = M\{x * [n] \cdot x[n+k]\} \tag{2}$$

Using the same principle, superior order cummulants can be computed.

Based on these observations, we can conclude that the spectral analyses that can be performed are as follows:

- mono-spectral analysis that uses the second order cummulant (self-correlation function given by (2)) that leads to the signal's mono-spectrum of the discreet time history of $x(n)$, i.e. the power spectral density [8]:

$$S_{2x}(f) = \sum_k C_{2x}(k) e^{\square\square - j2\pi fk}, \qquad k \in (-\infty; +\infty) \tag{3}$$

- bi-spectral analysis that uses the third order cummulant (given by (3)) that leads to the signal's bi-spectrum of the discreet time history of $x(n)$, [61]:

$$S_{3x}(f_1, f_2) = \sum_k \sum_r C_{3x}(k, r) e^{\square\square - j2\pi f_1 k} e^{\square\square - j2\pi f_2 r}, k, r \in (-\infty; +\infty) \tag{4}$$

Acting similarly, we can produce the superior orders cummulants as well. Some quotes are now necessary:

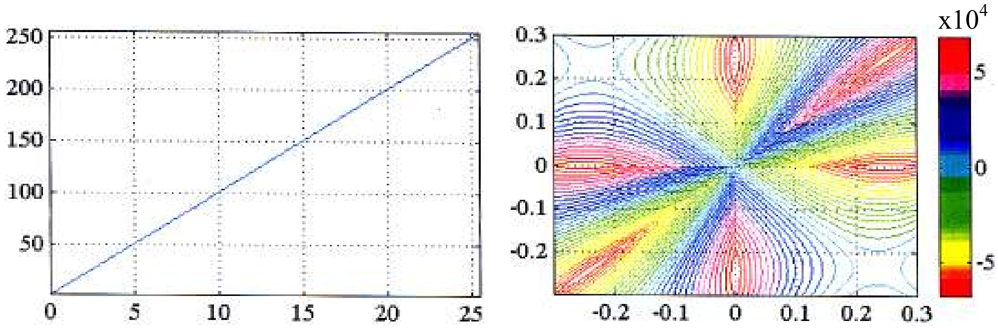
- the order j of the multi-spectrum is given by the number of frequency-type arguments, f, i.e. the tri-spectrum has three arguments: f_1, f_2, f_3.
- the order j of the multi-spectrum is given by the $j+1$ order of the cummulant, i.e. the third order cummulant computes the bi-spectrum;
- if the signal is given as a continuous time history, instead of finite sums the corresponding integrals are to be used; nevertheless, the same multi-spectra will be obtained but they are now continuous (due to $x(t)$ instead of $x(n)$)
- the bi-spectral analysis is used to separate the linear part from the non-linear one of a given signal;
- the tri-spectral analysis is useful when separating the noise from a given signal.

From the utility point of view, performing a bi-spectral analysis is enough most of the time to get satisfactory results within the field of research of the mechanical parameters.

We can conclude that the noises could be recognized using either bi- or tri-spectral analysis. On the other hand, the operator should be aware of the sources of the noises. Moreover, the bands the noises are occupying should be chosen wide enough to make the filtration possible while keeping in mind that to wide bands of filtration could affect the useful signal. Therefore, the first step that should be taken when choosing the right cummulant is to establish if the signal had or hadn't non-linear components. This is the reason that, most of the time, the third order cummulant (bi-spectrum, as given by (3)) is the right one if finite-difference equations were used.

If the third cummulant will be void (both amplitude and phase are null, which means that their charts are empty) then the signal lacks of non-linear components. If the above mentioned charts (fields) are not empty (fig. 1), then the signal contains non-linear components.

The bi-spectral analysis has the advantage that it provides an overall view of the analyzed signal and valuable information with respect to the filtering necessity and type of the filter to be used.



non-linear signal

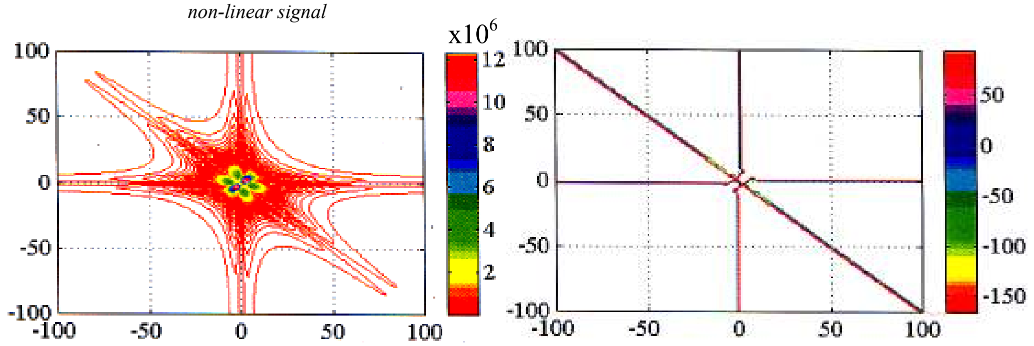


Figure 1: Bi-spectral analysis of a signal with non-linear components

4. MULTI-SPECTRAL ANALYSIS OF THE MEASURED SIGNAL OF A SELF-GENERATED TORQUE

To determine the self-generated torque within a 4x4 vehicle's driveline we proceeded in measuring some typical parameters at different points of the transmission. One of these parameters was the self-generated torque on the propelling shaft of the front axle of a 4x4 military vehicle.

The first analysis we made was the mono-spectral one.

At the first glance we can notice that signals are quite smooth (they look "quiet", not too much noise involved). We can also notice that the energy is mostly dissipated on low frequencies, next to the fundamental. That leads us to an important conclusion: the signal is not susceptible to contain non-linear components. Nevertheless, we can't be sure of that, since the FFT had frozen the signal in time. A more comprehensive analysis will be given by the multi-spectral analysis (bi-spectral in this case) to identify certain frequencies that dissipate important energy. Consequently, if noises occurred, we would use typical filters to eliminate them.

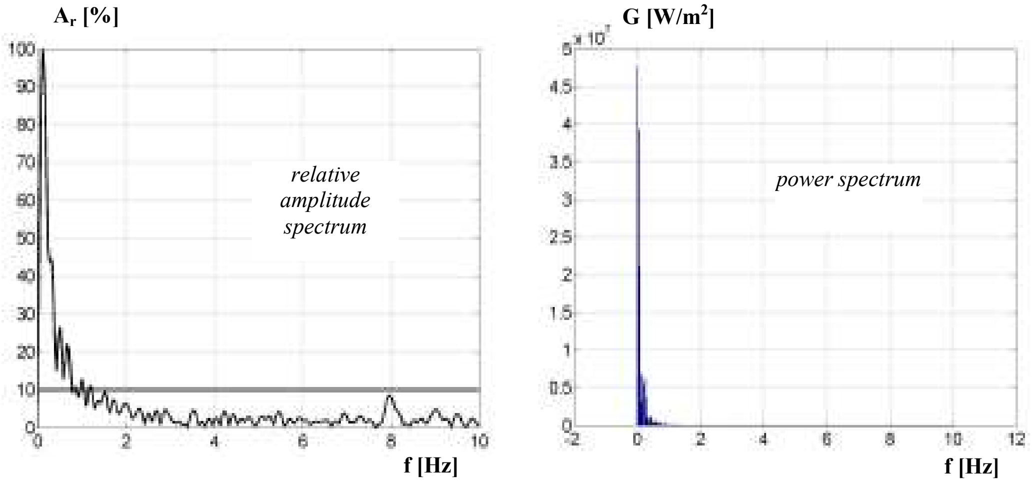


Figure 1: Frequency analysis (relative amplitude spectrum and power spectrum of the self-generated torque)

In this respect, the bi-spectral analysis of the same signal is given in fig. 2. We should mention that, in our complete research, we have developed the above-mentioned analysis for all the performed tests. Therefore we can say that all the signals we have analyzed had the same behavior like the one depicted in fig. 2. Even the classical spectral analysis "told" us that the signal is somehow linear, this analysis shows that we should filter the achieved signal, since some non-linear components are obvious, even not too much.

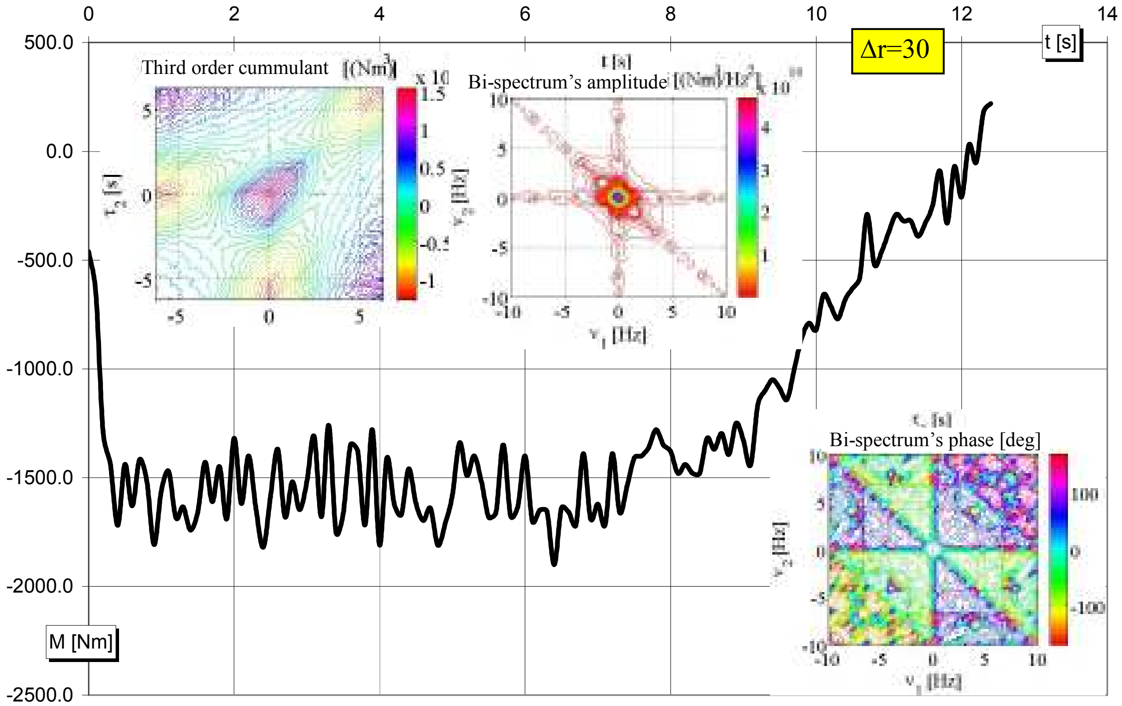


Figure 2: Bi-spectral analysis of the self-generated torque's signal on the driving shaft of the front axle (not filtered signal)

The FFT analysis didn't show any peculiar frequency band that should be removed. According to the bi-spectral analysis we can see that we deal with a sort of a "white" noise, spread across the all frequency spectrum. Hence, a specialized, digital filter won't help at all; on the contrary, it will remove useful parts of the signal.

According to [9], the best results could be obtained with a *Savitzky-Golay* finite impulse response (FIR) filter, also known as a polynomial digital smoothening filter. These filters are used when a smoothening procedure is needed, especially for those signals that aren't strongly affected by noises. They are better when IIR (infinite response filter) filters aren't suitable. Moreover, *Savitzky-Golay* filters are optimal from the point of view of minimization of the approximation error since they use the least square method [8].

Fig. 2 and 3 provide a comparison between the bi-spectra of the self-generated torque's signal before (fig. 2) and after filtering it (fig. 3). It is easily noticeable that we could get a good linearization of the signal, both from the curve's shape and the bi-spectrum's amplitude's chart (field). The filtered signal's field of the bi-spectrum's amplitude is much cleaner compared to the non-filtered correspondent. Moreover, the filter's order was properly chosen. Too high orders lead to very smooth yet non-realistic curve [8].

A few more observations should be made: as we mentioned, the field of the bi-spectrum's amplitude provides information with respect to the non-linear components. The more "populated" this field is, the more energy is dissipated on the frequencies of the non-linear components. On the other hand, the amplitude of the frequencies of the non-linear component is also important. According to the neighboring color strip, higher energy dissipation corresponds to deep purple region of the color strip. Attention should also be paid to the absolute values of the amplitude. We can see that, in the depicted case, there is no important dissipation of energy on the non-linear components. The conclusion is very simple: the signal has non-linear components but their importance is insignificant.

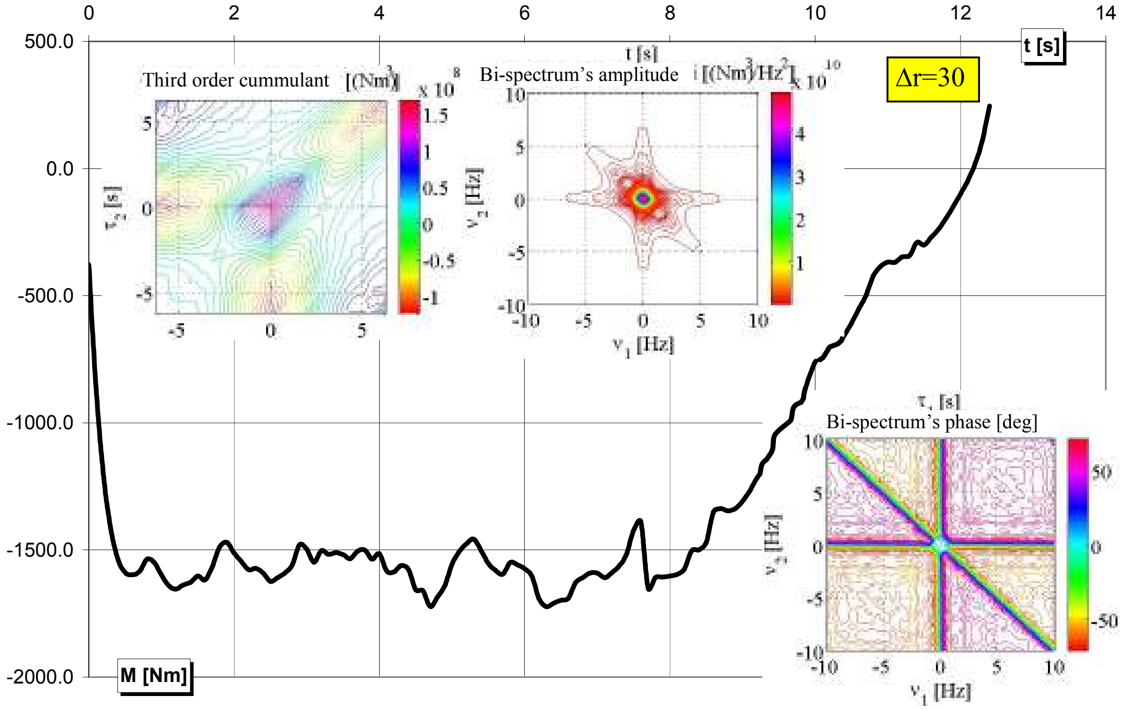


Figure 3: Bi-spectral analysis of the self-generated torque's signal on the driving shaft of the front axle (signal filtered with a 3rd order Savitzky-Golay filter)

5. CONCLUSION

The all-wheel driven transmission yet has a big problem: the self-generated torque that occurs inside the driveline. The self-generated torque generates the loop power-flow.

Loop power-flow within an automobile's transmission is generally due to the different lengths of the trajectories the vehicle's wheels are covering. To compute the power loss due to this phenomenon we needed to measure some typical mechanical parameters on different key-points of the driveline (angular speed and torque, specifically).

Following the mono-spectral analysis we concluded that signal needs some filtration although it doesn't have too peaky non-linearity.

After the bi-spectral analysis we noticed that the non-linearity couldn't be considered as insignificant; hence, some filtration should be performed. Also, this analysis told us that the noise is rather "white" and a specialized filter would rather damage the dynamic serials. Finally, we decided that the most suitable filter would a 3rd order

Savitzky-Golay filter. After filtration, the signal lost most of its noise while keeping its useful core. That can be seen in fig. 2 and 3.

So, in this respect, we think that we used the best way to improve the quality of the signal without loosing its main core, and we could perform further investigation with respect to the self-generated torque and the power loops within a 4x4 automotive driveline.

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