Hári, László Róbert

# Analysis and Simulation of Non-Stationarities in the Time-Frequency Domain of Road-Induced Vibrations

Ph.D. Theses

Supervisor: Prof. Dr. Földesi, Péter

Multidisciplinary Doctoral School of Technical Sciences

Széchenyi István University

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# Summary

The Introduction excerpted the bibliographic sample analyses [1, 2] leading to the motivation of the current dissertation, summarized in a Proposition.

**Proposition.** Based on the heterogeneous research topics of road vehicle vibration studies, the lifetime of installed vehicle components and their design to take on loads from amplitude- and frequency modulated excitation, as well as, the avoidance of aversion in passenger comfort, and the vibration protection of transported loads are central research subjects. Instead of studying the individual subsystems of the road–vehicle–cargo system, it can be imperative to establish a standardized methodology, since the final source of excitation is itself the road-induced vibration. ■ *Ref.*: [1, 2]

Non-stationary simulations gained increasing attention, not only in Packaging vibration testing (PVT) but in disciplines concerned with the analysis and synthesis of Road vehicle vibrations (RVV). The limitations of Power spectral density (PSD) based simulations have inherent contrast to real-world RVV. That is, relying on a single PSD, or Discrete Fourier transform (DFT) profile, substantively assumes the stationarity of process; hence, the inverse Fourier transformation can produce only stationary signals, when joint with a uniformly distributed random phase series. This deviation is illustrated in Fig. 1, where the lack of transients in the synthesized signal is to be noted. In effect, if a dynamic system has to be designed for taking on transient loads, the adequacy of stationary simulations is seriously limited either as verification in the modeling phase, or as validation in the post-design or pre-release phases.

The dissertation presented various occasions that the spectral content of RVV is far from an autonomous process, far from being avoid of changes. It is therefore rightly to assume non-stationarity in the time-frequency domain structure of RVV, as well. The Chapter, Spectral non-stationarity, has presented that the STFT of measured RVV show up varying spectral characteristic, i.e., the DFT profiles and its spectral moments are non-stationarity over time, allowing the 1$^{st}$ thesis [3]. The example of Fig. 2 is a good depiction of drive-train related frequency modulations, furthermore, significant difference in spectral structure at stops, or increased noise levels at various subsections of the recording.

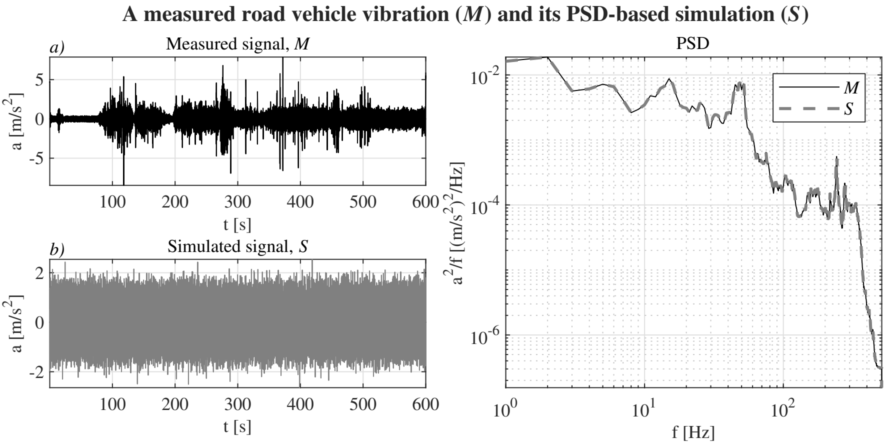


Figure 1: Comparison of real-world RVV with its PSD-based simulation. Pane *a)* shows the first 10 min of measurement A from Chapter, Spectral non-stationarity, and its Power spectral density in pane *c)* via *black solid* line. The PSD of the measured signal, *M*, had been used to simulate a random signal with uniformly distributed random phase in each iteration of the inverse Fourier transform, for 600 s in total. The resulted synthesized signal, *S*, can be seen in pane *b)* in the time domain, and its re-computed PSD in pane *c)* via *gray dashed* line. The overlap of the two PSD profiles are to be noted, only the PSD of the simulated signal resulted a 28-order smaller difference in the last bin.

**Thesis 1.** I have presented that the shape of amplitude spectrum function is not constant over time, due to the variation of the spectral shape manifested in the time-frequency domain, which is due to transient events, and harmonic excitation in accordance with the driving speed, compared to the spectral shapes of the steady-state vibration intervals. The changes, therefore, occur locally on the time or space horizon of the journeys, thus, for practical reasons it is reasonable to separate them into homogeneous intervals. ■ *Ref.*: [3]

The time-domain of RVV has been thoroughly investigated by scholars, as the author had reviewed those methods in [4]. In order to find homogeneous sections within RVV recordings, various changepoint- or event-detection algorithms have been published. The Chapter, Analysis of prior algorithms, has analyzed the steps of available processes since only a few insights under the hood of such algorithms are provided. As it has turned out, the reproducibility can be easily challenged in most of the cases.

**Thesis 2.** I have observed that previous segmentation algorithms have been uncalibrated and designed along heuristic considerations in several cases. Calibration of detection algorithms is essential when investigating road-induced vibrations. For verification purposes, the segment length distribution should be investigated on a test sample, as a necessary complementary investigation beneath the receiver operating characteristic. ■ *Ref.*: [4]

The bibliographic sample analyses has shown, that PVT originates in the *measurement and analysis* of RVV, which soon expanded its scope to *simulations* [2], foreshadowing the aims of current work embracing the 5$^{\text{th}}$ Thesis. The merit of a second kind has also challenged a preconception. That is, the investigations had been pre-dominantly limited to the time domain, whereby spectral non-stationarities are, at the best, only mentioned. Therefore, it had to presented how the STFT structure are inherently responsible for time domain non-stationarities. The novel algorithms have been developed in Chapter, Development of segmentation, such as the Multiple hypothesis testing by paired $t$-tests as published in [5]:

$$\begin{cases} H_0^{(j)} : \overline{d_j} = 0; \\ H_A^{(j)} : \overline{d_j} \neq 0, \end{cases}$$

where $d_j = a_i - a_{i+1}$, with $a_i$ denoting the DFT coefficients in the $i$-th timepoint of the STFT. By two-sample $t$-tests, published in [6]:

$$\begin{cases} H_0^{(i)} : \overline{a}_{i,k} = \overline{a}_{i,k+1}; \\ H_A^{(i)} : \overline{a}_{i,k} \neq \overline{a}_{i,k+1}. \end{cases}$$

where $a_{i,k}$ denotes the DFT coefficients in the $i$-th timepoint of the STFT through $k$ frequency components.

**Thesis 3.** The surface formed by short-time Fourier amplitude spectrum can be segmented in the time-frequency domain due to the temporal variation of the inherited spectral shape. This can be done by applying paired-sample- and two-sample $t$-tests to the Fourier coefficients of adjacent-to-adjacent amplitude spectra. ■ *Ref.*: [5, 6]

The spectral non-stationarity has been also supported by a conventional method applied in a novel context, as discussed in the Section, CUSUM-type changepoint detection [7]. While the algorithm needed custom implementation in lack of command-line availability, the novel characterization of the STFT plane in the forms of spectral moments was also necessary. The Chapter, Calibration of segmentations, has presented that the Segment length distributions are a necessary company to Receiver operating characteristics in the verification, leading to the next thesis [8].

**Thesis 4.** I have shown that there exists a significance level and it can be determined for so-called *CUSUM* recursive algorithms—which algorithm searches for the local extrema of the cumulative sum of deviations from the total mean—which significance level minimizes the difference between the theoretical distribution of the segment lengths of the test signal and the segment length distribution between the detected boundary points. ■ *Ref.*: [7, 8]

While in Multiple hypothesis testing, the adjustment of significance limit is often advised; it has been shown, the Bonferroni- and Holm–Bonferroni correction are too strict in the long term for RVV segmentation purposes.

The developed changepoint detections could have been used on the sole reason of segmentation as the basis of further quantitative analyses. It has been shown, that the segment length- and RMS distributions did not allow to assume a bi-uniform joint distribution. That is, not any RMS content can be imagined on arbitrary lengths. Therefore, the simulation of non-stationary

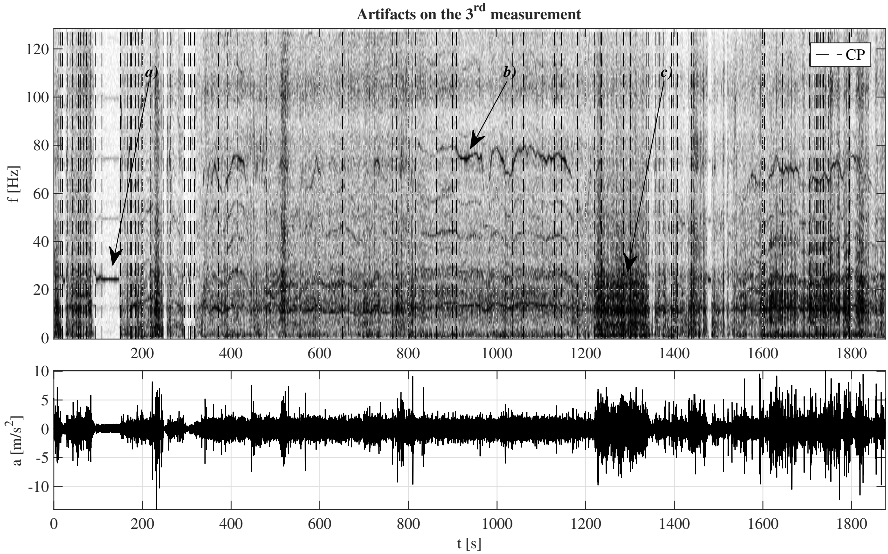


Figure 2: Artifacts on the short-time Fourier transform of the $3^{rd}$ measurement. The gray-scale surface is overlayed by segment borders (*dashed line*) in the upper pane. Various effects can be seen in the spectrogram, such as *a)* constant harmonic excitation and its harmonics, possible one sub-harmonic; *b)* drifting harmonic excitation; *c)* broad-band excitation for a prolonged period dominated by frequency range app. $[1, 50]$ Hz between $[1220, 1320]$ s.

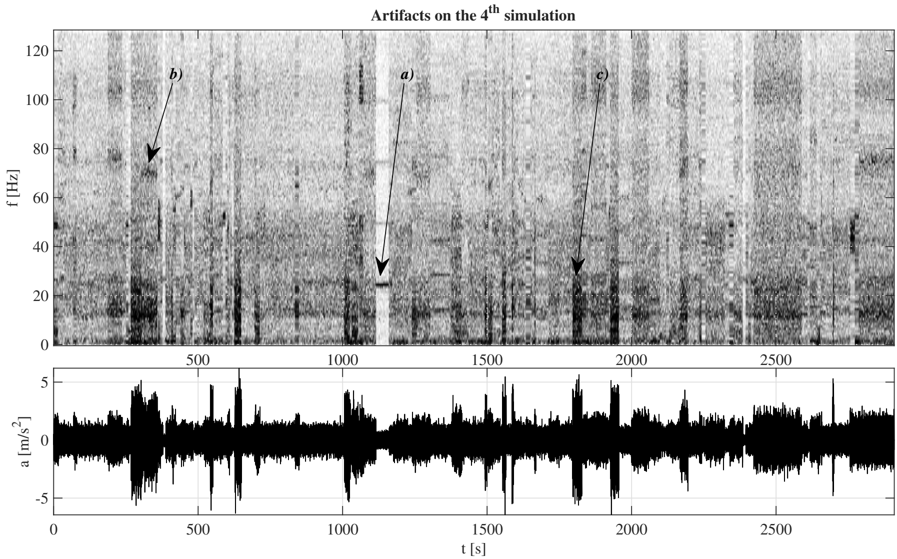


Figure 3: Artifacts on the short-time Fourier transform of the $4^{th}$ simulation. In the upper pane: *a)* simulated stop, i.e., constant harmonic excitation with harmonics, *b)* harmonic component with possible sub-harmonincs blended in background noise, *c)* broad-band noise.

RVV followed the segmentation.

Each of the prior three segmentation methods can be used in a modular manner during the simulation, Probability-based Spectrogram Synthesis (PBSS). For an eased acceptability, the conventional CUSUM algorithm had been inherited [9]. Its further advantages also emanates from the joint probability distribution of segment lengths and -RMS. That is, every new *segment-in-simulation* has a length and RMS target value according to random variables. The key idea in the synthesis of segments excavated that the amplitude spectrum values in each frequency bin can be fitted with individual distributions from the *segment-to-simulate*. That is, the synthesis is directly accomplished in the time-frequency domain. Such a simulated signal is presented in Fig. 3.

**Thesis 5.** A simulation routine can be constructed that can reflect spectral variations in the time-frequency domain in a realistic manner; which simulates an arbitrary number of different time-frequency domains from a single measurement realization; furthermore, which simulates aggregate statistical properties of the registered road vehicle vibrations. Verifying this claim, I have presented the *Probability-based Spectrogram Synthesis* procedure for simulating the $2^{\text{nd}}$, $3^{\text{rd}}$, and $4^{\text{th}}$ spectral moments. Practical implications of the thesis are:

5.1 Changepoints in the time-frequency domain can found simultaneously for transient events, changes in the root mean square of the signal, and the appearance of harmonic excitations in the road vehicle vibration signals.

5.2 Methods relying on magnitude modulation bypass the need for *a priori* and heuristic adjustment of many parameters.

5.3 Road vehicle vibrations can be directly simulated in the time-frequency domain.

5.4 Modeling and simulation based on measured data outperforms in variability the time-history replication method. ■ *Ref.*: [9]

It allows not only to achieve random segment length and -RMS pairs, but the modeling of STFT values are simulated in *each second of each segment of each simulation*. Therefore, given only one realization of RVV measurement, arbitrary number of different artificial RVV can be obtained. Furthermore, given numerous RVV measurements, their pooled sampling is applicable.

Not only a simulation could follow the segmentation. In the author's opinion, the composition of databases storing DFT characteristics will be sooner or later necessary. In this problem, however, it can be rightly supposed that the similarity of spectral profiles has to be investigated. In this manner, the hierarchical clustering of DFT profiles in the STFT had been investigated in the Chapter, Clustering spectrums. While this is based on a simplistic idea, no spectral clustering has appeared in the concerned discipline of PVT [10].

**Thesis 6.** In binary hierarchical clustering of amplitude spectrum of road-induced vibrations, most likely the cosine distance maximizes the number of clustered elements and minimizes the scattering in-between clusters. ■ *Ref.*: [10]

As final thoughts, the current dissertation presented, how non-stationarity in RVV can be approached from the time-frequency domain. The changes in spectral characteristics can be found by the new algorithms. Furthermore, the presented simulation, PBSS, allows the non-stationary STFT simulations. With the above theses and corresponding methods, the practitioners have new tools to investigate dynamic systems subjected to road-induced vibrations.

# Publications


[1] László Róbert Hári. "Keyword Co-occurrence Analysis of a Packaging Vibration Testing Relevant Sample". In: *16th International Bata Conference for Ph.D. Students and Young Researchers*. Vol. 16. Zlín, Czech Republic: Tomas Bata University, 2020, pp. 187–201. ISBN: ISBN: 978-80-7454-935-9. DOI: `https://doi.org/10.7441/dokbat.2020.16`.

[2] László Róbert Hári. "Timeline-based Network Analysis of a Publication Sample Related to Packaging Vibration Testing". In: *Business Logistics in Modern Management*. Osijek, Croatia: Josip Juraj Strossmayer University of Osijek Faculty of Economics in Osijek, Oct. 2020. ISBN: 1849-6148 (Online).

[3] László Róbert Hári. "Spectral Non-Stationarity in Road Vehicle Vibrations (in review)". In: *Periodica Polytechnica Transportation Engineering* -.- (), pp. –.

[4] László Róbert Hári. "Event Detection Algorithms in Packaging Vibration Testing: An Analytic Review". In: *Business Logistics in Modern Management*. Osijek, Croatia: Josip Juraj Strossmayer University of Osijek Faculty of Economics in Osijek, Oct. 2021, pp. 453–472. ISBN: 1849-6148 (Online).

[5] László Róbert Hári. "Multiple Hypothesis Testing by Unpaired Samples for Indexing Changepoints in a Road-induced Vibration Signal". In: *University Politehnica of Bucharest - Scientific Bulletin*. Series D 83.3 (2021), pp. 17–28. ISSN: 1454-2358.

[6] László Róbert Hári. "Segmentation of a Road Vehicle Vibration Signal Using Multiple Comparison Procedures between Paired Samples". In: *Tehnicki Vjesnik - Technical Gazette* 28.5 (Oct. 2021). ISSN: 13303651, 18486339. DOI: `10.17559/TV-20200122112551`. URL: `https://hrcak.srce.hr/261336` (visited on 01/03/2022).

[7] László Róbert Hári and Péter Földesi. "Evaluation of a CUSUM-type Changepoint Detector Applied in the Time-Frequency Domain of Synthetic Road Vehicle Vibrations (in Print)". In: Miskolc, Hungary, Sept. 2022.

[8] László Róbert Hári and Péter Földesi. “Calibration of Two Novel Segmentation Approaches by Synthetic Road Vehicle Vibrations (in review)”. In: *Tehnicki Vjesnik - Technical Gazette* -.- (), pp. –.

[9] László Róbert Hári. “Spectral Moment Segmentation and Spectrogram Synthesis for Simulation of Road Vehicle Vibrations”. en. In: *Mechanical Systems and Signal Processing* 180 (Nov. 2022), p. 109408. ISSN: 08883270. DOI: 10.1016/j.ymssp.2022.109408. URL: https://linkinghub.elsevier.com/retrieve/pii/S0888327022005350.

[10] László Róbert Hári and Péter Földesi. “An Approach for Hierarchical Clustering of Road Vehicle Vibration Spectrums (in print)”. In: Miskolc, Hungary, Sept. 2022.

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