# Review paper on road vehicle vibration simulation for packaging testing purposes

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Inefficient packaging constitutes a global problem that costs hundreds of billions of dollars, not to mention the additional environmental impacts. An insufficient level of packaging increases the occurrence of product damage, while an excessive level increases the packages' weight and volume thereby increasing distribution cost. This problem is well known and for many years engineers have tried to optimize packaging to protect products from transport hazards for minimum cost. Road vehicle shocks and vibrations, which is one of the primary causes of damage, need to be accurately simulated to achieve optimized product protection.

Over the past 50 years, road vehicle vibration physical simulation has progressed significantly from simple mechanical machines to sophisticated computer-driven shaking table. There now exists a broad variety of different methods used for transport simulation. Each of them addresses different particularities of the road vehicle vibration. Because of the nature of the road and vehicles, different sources and processes are present in the vibration affecting freight. Those processes can be simplified as the vibration generated by the general road surface unevenness, road surface aberrations (cracks, bumps, potholes, etc.) and the vehicle drivetrain system (wheels, drivetrain, engine, etc.).

A review of the transport vibration simulation methods is required to identify and critically evaluate the recent developments. This review begins with an overview of the standardised methods followed by the more advanced developments that focus on the different random processes of vehicle vibration by simulating non-Gaussian, non-stationary, transient and harmonic signals. As no ideal method exists yet, the review presented in this paper is a guide for further research and development on the topic.

KEY WORDS: road vehicle vibration, packaging vibration simulation, non-stationary vibration, non-Gaussian vibration, transient simulation

## INTRODUCTION

Every product, manufactured or grown, is transported by road at some point between the production site and the consumer. Goods are protected from shocks and vibration encountered during distribution using protective packaging. Both insufficient and excessive packaging are costly; insufficient packaging increases the occurrence of damage incident and excessive packaging increases the volume and weight of packages. To reduce these costs, the design of packaging must be optimised to ensure that products remain undamaged during their distribution using the minimum volume and weight of cushioning material.

Simulating the complex shocks and vibration induced to products during transportation is a necessary step in the development of packaging to test its effectiveness in protecting the

product [1]. However, the accuracy of the simulation itself is critical for packaging optimisation. Severe simulations will ensure the product's integrity but result to the use of excessive cushioning material and has a direct impact on distribution costs, moderate simulations result in insufficient protection. Therefore the simulation has to recreate the different shock and vibration elements generated by the vehicle. These include vibration generated by road roughness, road surface aberrations (cracks, bumps, pothole, etc.) and vehicle drivetrain system (wheels, drivetrain, engine, etc.).

In the last few decades, various methods have been developed to improve the accuracy of vehicle vibration simulation. Because of the complex nature of this multi-process type of vibration, these methods are varied and each method attempt to address the diverse limitations of others. Their frameworks are also different and include heuristic-based methods to more statistical and signal processing-based methods. A review of five simulation methods was presented by Richards [2] in 1990, but many new methods have been developed since then. Another review is therefore needed in order to present an overview of the different simulation approaches available today. The methods proposed by standards organizations are first discussed. A considerable amount of literature has been published on the shortcomings of these standard methods and present alternative simulation methods. These alternatives are separated into five categories: time history replication, non-Gaussian simulation, non-stationary simulation, transient events simulation and harmonic simulation.

## STANDARDISED METHODS

Eccentric cams fixed under a testing table were one of the first devices used to simulate transport vibration. This excitation mechanism was simple. When the cams were spinning fast enough, the table detached from the cam at each rotation creating repetitive shocks, as described in the ASTM Standard D999-08 [3]. This method is still used today [4], even if this method was later recognized to produce repetitive shocks rather than actual transport vibration. Hence Kipp [5] recommends to be very cautious about extending any conclusions drawn from the technique.

The natural evolution of the test method was to use single frequency vibration to avoid any shock events in the simulation as described in the ASTM standard D3580-95 [6], ISO IEC-60068-2-6 [7]. The excitation signal for this method consists of sweeping the sinusoidal excitation frequency during the test. Once again, this method is criticized because it does not reproduce the randomness of the road excitation. Many have suggested using it as an investigation and design tool rather than a packaging performance test [5, 8, 9].

The limitations of these standards led to the use of random vibration as a standard road vibration simulation in the early 1980s, described in standards: ASTM D4728-06R12 [10], MIL-STD-810F [11], ISO 13355:2003 [12]. These procedures produce random Gaussian vibration from different target Power Density Spectra (PDSs) representing different types of vehicle. These PDSs can be obtained from measurements on one or more vehicles or from road profile surveys and vehicle dynamic models. However, Rouillard and Sek [13] stated that the vehicle measurement based PDS method gives better results since they do not require modeling approximation.

An advantage of this method is the apparent possibility to shorten the testing time by increasing the intensity of the simulation. The relationship between actual and test duration is given by the Basquin model:

$$\frac{t_j}{t_t} = \left(\frac{a_t}{a_j}\right)^k \qquad \text{(eq. 1)}$$

Where $t_t$ is the test duration; $t_j$ is the actual journey duration; $a_t$ is the test intensity; $a_j$ is the actual journey intensity; and $k$ is a constant associated with the material/product tested, where $k = 2$ [14, 15] and $k = 5$ [16] are generally used.

## Shortcomings of Standardized Random Vibration Testing

Random vibration testing based on target PDSs is a common simulation method to test packaging efficiency. However many researchers challenge the validity of the Gaussian nature of the vibration produced by this method (even if many standards use this method).

To understand the major deficiency of this method, the process that underpins the generation of the vibration signal must be understood. The synthetic signal (FIG. 1 c) is created from a target PDS of a road vehicle vibration signal (FIG. 1 b) to make sure it has the specific frequency distribution contained in the real vehicle excitation. But PDSs do not have any time information; they only provide the average signal power density as a function of frequency. Therefore to create a random signal, the PDS is transformed into an amplitude spectrum with a random phase. This spectrum is then transformed into the time domain via an Inverse Fourier Transform. This produces a random Gaussian signal that corresponds to the specific frequency spectrum.
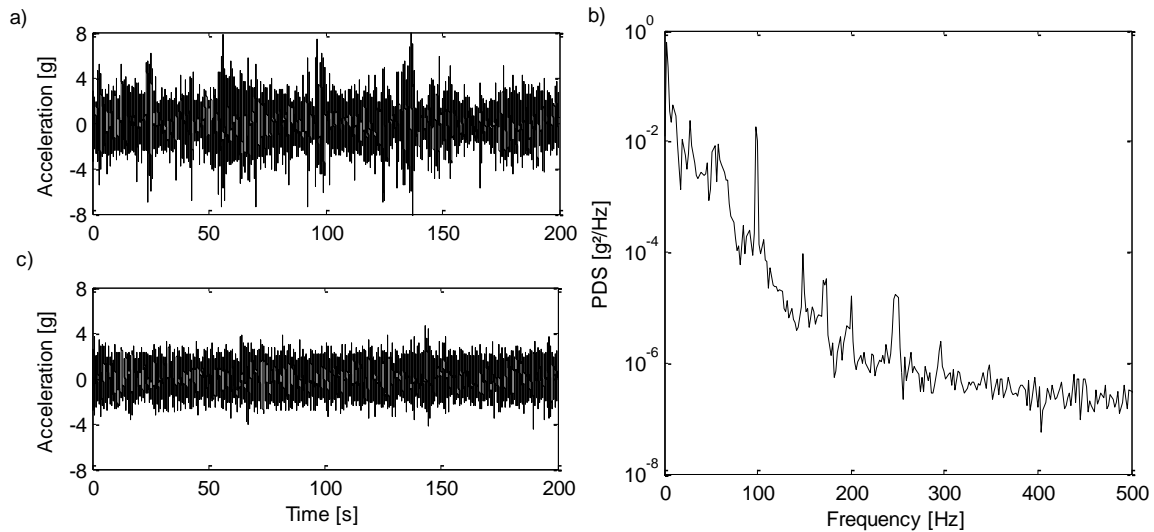


FIG. 1 Gaussian signal synthesis of a road vehicle vibration signal: a) vehicle signal; b) PDS of the vehicle signal used for the synthesis; c) Gaussian synthetic signal

The problem is that the steady-state nature (constant vibration intensity level i.e. Root Mean Square (RMS) value) of the Gaussian signals produced by this method does not represent realistic vehicle vibration. Vibration fluctuations caused by variations in the road roughness (profile characteristics) and vehicle speed cannot be represented by a constant RMS value signal. The high amplitude events unrepresented in the PDS are not present in the signal either (FIG. 1 a and c). Therefore, vibration tests based on PDS alone lacks high amplitude events which can have a significant effect on product damage [9, 17, 18].

The target PDSs provided in the standards to generate the random signal also concern researchers because they are not necessarily representative of real vehicle vibration. These

functions oversimplify vehicle dynamic behavior. They are rough representations which include all vehicle dynamic behavior and the PDS shape is not accurately represented [13, 19]. This has a serious consequence in that the energy of the simulated signal is spread across a broader frequency band rather than focused around a narrow frequency region as is the case for real vehicles which exhibit mechanical resonances [19].

An important shortcoming also comes from the time compression. The artificial signal amplifications that reproduce the high amplitude events of the vehicle excitation are normally distributed (Gaussian) which is not the case with vehicle excitation. Therefore high amplitude events have much higher occurrence in the time compressed signal.

## TIME HISTORY REPLICATION

The more candid way to reproduce vehicle vibration without all the shortcomings of the PDS based Gaussian reproduction is to play back the time history vibration recorded from vehicle measurements on a shaker. But as simple as this solution may be, it presents the following fundamental issues.

One single time history replication has no statistical significance. In other words, using the time replication of one journey is only a sample of all possible journeys (population). This specific journey may have been more or less severe than usual (statistical extremum) and there is no way to verify this unless many journeys are recorded. But the issue of dealing with several journeys is how to select a typical one in an objective manner remains unresolved.

The solution could be to replicate different time histories of various journeys in a series to increase the test significance. But this requires extremely long testing time and taking into account that the time history signal cannot be significantly compressed [5], it is unrealistic to use a series of time history for packaging testing purpose.

## NON-GAUSSIAN SIMULATION

As previously explained, the PDS-based vehicle vibration replication method generates normally distributed (Gaussian) acceleration signals. This is problematic because road vehicle vibration is well known to be non-Gaussian, more specifically leptokurtic (high kurtosis value). Therefore for the same RMS value, a Gaussian signal has a lower maxima than the leptokurtic signal [18, 20].

Some researchers worked on this issue by reproducing random vibration from a target PDS using different distribution (non-Gaussian) [21-24]. One of the methods used to recreate non-Gaussian random vibration based on a spectrum is to distort the waveforms using zero-memory nonlinear (ZMNL) monotonic function [25]. However this operation is made in the time domain so the spectral proprieties of the synthetised signal are not necessarily conserved. To control the spectrum and the kurtosis of the synthetic signal, Van Baren proposes in his US patent [26] to use adaptive filters.

The main limitation of the non-Gaussian simulation, however, is its inability to reproduce the non-stationary nature of the vehicle excitation. Since the vehicle speed and the roughness of the road pavement vary throughout a journey, the vehicle excitation is therefore non-stationary [2]. This non-stationarity can be evaluated with the variation in time of the statistical moments of the signal. For instance when the mean value and the RMS value

(standard deviation) of a signal do not vary in time, the signal is called weakly stationary or stationary in the wide sense. However, because it is most of the time impractical to prove that a signal is strongly stationary (where all the possible statistical moments are time invariant), Bendat and Piersol [27] propose that: "for many practical applications, verification of weak stationarity will justify an assumption of strong stationarity."

According to that definition, the non-Gaussian simulations described above are necessarily stationary because they are based on a fixed distribution, so the statistical moments of the signal describing this distribution are time invariant. In that sense, this type of simulation does not faithfully represent road vehicle vibration which is non-stationary.

## SIMULATING NON-STATIONARITY

Simulating the non-stationary nature of vehicle vibration has been addressed by several researchers. They all use a similar approach of decomposing the signal into stationary segments. Several methods have been used to decompose a vehicle vibration signal into stationary segments. The following section presents a review of methods used to decompose the signal.

It is interesting to note that decomposing a road vehicle vibration signal into Gaussian segments has shown that the non-Gaussianity of the signal is not inherent to the vehicle excitation but it is caused by the fluctuation of the RMS values of the signal, i.e. its non-stationary nature [17, 18, 28-31]. In other words, it is not the road profile and the vehicle dynamic behaviour that makes the vibration non-Gaussian, but is caused by the sequential combination of random Gaussian process of different amplitudes. This further justifies the use of signal decomposition to accurately simulate road vehicle vibration.

### Split Spectra Decomposition

One of the first initiatives to simulate the non-stationary nature of road vehicle vibration is to decompose the signal into low and high amplitude events. The idea is to calculate two PDSs based on 70 % of the vehicle vibration signal with the lowest acceleration levels and on 30 % with the highest acceleration levels [32, 33]. This is based on the hypothesis that the low level spectrum represents the vehicle response to road profile random variations and the high level spectrum represents the response to transient events such as speed bump, cracks, potholes, etc.

However, selecting a signal amplitude to effectuate the separation to calculate the PDS is subjective. For instance Wallin [34] used a 80 %- 20 % ratio and Kipp [9] used a three way split spectra for 70 %, 25 % and 5 % of the signal. Kipp [9] even went further in the number of split spectra by proposing the probability split spectra defined as: "the probability that an encountered PDS level will be at or below the profile based on all data events recorded." For instance, the profile proposed by him is 100 %, 99 %, 95 %, 90 %, 80 % and below. Unfortunately, there is not enough published information on the implementation and validation of this method to properly assess this.

Wolfsteiner and Breuer [35] also proposed to decompose rail vehicle vibration into several PDSs. This decomposition seems to be in the time domain, but once again limited information exists about how it was achieved. Therefore, it is difficult to assess the potential of this technique, but according to the authors, it is an effective method to use for finite elements analysis simulation purposes.

## Random Gaussian Sequence Decomposition

Another approach to deal with non-stationary vehicle vibration is to assume that the PDS shape is constant and to decompose the signal into Gaussian segments of different amplitude. The Random Gaussian Sequence Decomposition (RGSD) was first proposes by Charles [17] and then implemented by Rouillard [18]. The general idea is to decompose a non-Gaussian distribution of the vehicle signal into several Gaussian distributions. As shown in FIG. 2, a leptokurtic normal distribution of vehicle vibration can be represented as a sum of Gaussian distributions.
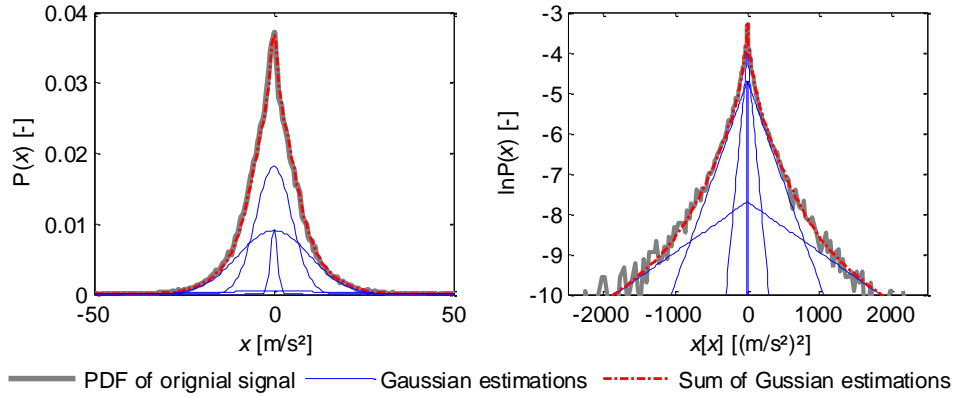


**FIG. 2** Gaussian decomposition in a linear scale on the left and a log scale on the right

The contribution of every sequence with its standard deviation $\sigma_i$ (also called RMS value) is weighted with a term called Vibration Dose $D_i$ to fit the signal distribution $p(x)$:

$$p(x) = \sum_{i=1}^{n} \frac{D_i}{\sqrt{2\pi}\sigma_i} \exp\left[-\frac{1}{2}\left(\frac{x}{\sigma_i}\right)^2\right] \qquad \text{(eq. 2)}$$

This Vibration Dose also describes the time fraction for which each Gaussian sequence exists. However it does not give any information about the sequences length and position in the signal. To provide this information, the Gaussian segments are identified in the time signal using a cumulative sum - bootstrap algorithm. It is shown that this algorithm is a robust and reliable technique to detect significant change in the statistics of the instantaneous acceleration magnitude signal [18, 30]. The results however are dependent of the signal length (window) used to calculate the RMS value [36]. A short window does not represent the true non-stationarities of the signal and a long window will not detect the short-duration non-stationarities.

The analysis of vibration measurements of different vehicles and roads shows that the statistical distribution of the Gaussian segments duration follows a hyperbolic curve. These measurements represent a variety of small utility trucks, vans, rigid trucks and semi-trailers with various suspension types and payloads riding on randomly selected poorly maintained local roads, country roads, urban roads and highways (motorways), located in Victoria, Australia. Further details on measurement conditions are given by Rouillard [18]. These measurement samples provide a good representation of roads in Australia and the conclusions drawn could be extended to other developed countries.

A non-stationary synthetic signal is recreated using the hyperbolic distribution of the segments duration combined with the RMS value distribution (based on the Vibration Dose)

to first produce a modulation function (FIG. 3 a). This modulation function is then multiplied by a random Gaussian function (created with the measurement PDS, FIG. 3b) to generate the synthetic non-stationary signal used for simulation purpose (FIG. 3 c).

The level of non-stationarity of a signal can be estimated using the ratio of the number of Vibration Dose to the expected number of Vibration Dose for a stationary signal [36].
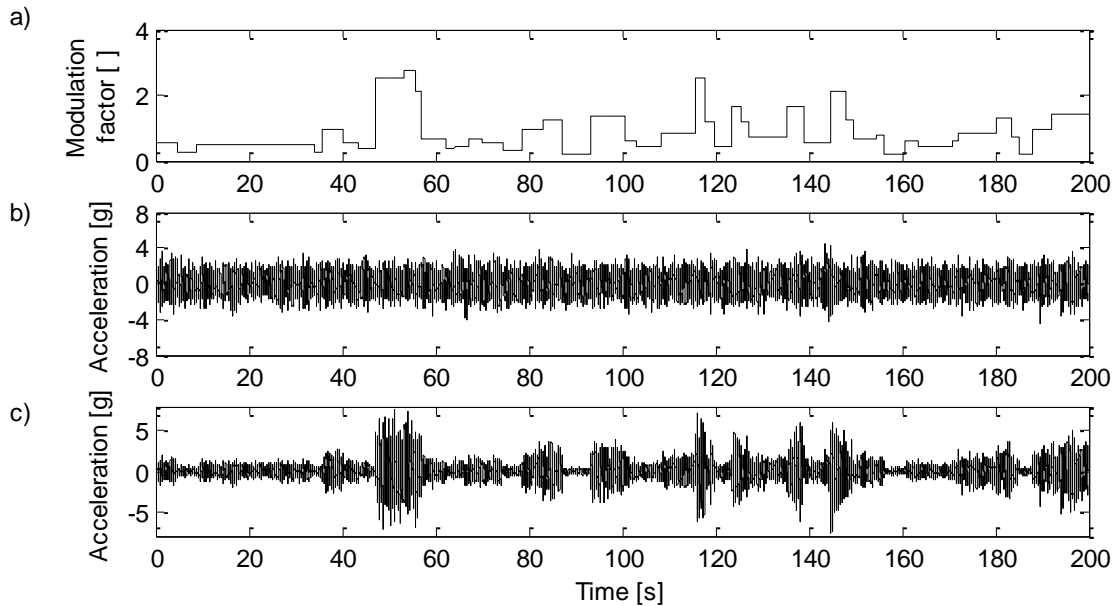


**FIG. 3** Random Gaussian Sequence Decomposition: a) modulation function; b) random Gaussian function; c) synthetic non-stationary signal

## Vehicle and Road Characteristics Based Simulation

Another similar simulation method to the RGSD is vehicle and road characteristics based simulation. This method, proposed by Rouillard and Sek [13], has the benefit of not requiring any road measurements to create a simulation. As with the RGSD, it uses a modulated random Gaussian function but it is entirely based on established models.

For instance the vehicle Frequency Response Function (FRF) is computed from parameters of different vehicle types published by Cebon [37]. The vehicle response PDS can be estimated by combining the FRF with the road elevation PDS curve [38] coupled with the vehicle speed [39, 40].

A transport journey vibration signal can be synthesised using known road roughness classification data and corresponding vehicle speed and segment durations. The vehicle speed dependence on the road roughness can be taken into account; such as higher speed on smooth roads or lower speed on rough roads.

This is a practical and affordable method to simulate vehicle vibration, but according to the author it is only a rough approximation of the reality since the signal is based on generic PDSs.
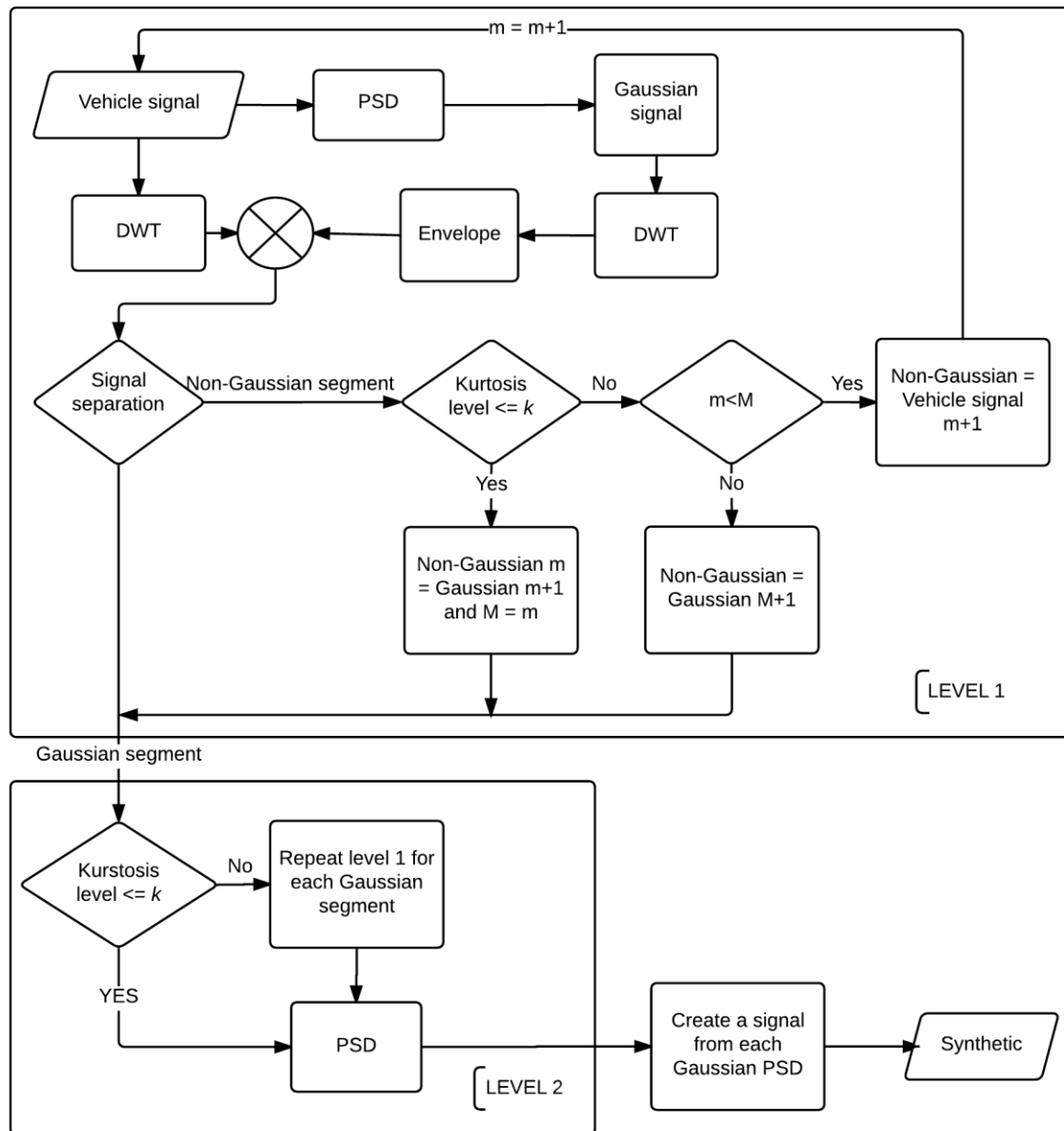
**FIG. 4** Flow chart of the Wavelet Based Gaussian Decomposition, reproduced from Griffiths [41]

## Wavelet Based Gaussian Decomposition

The Discrete Wavelet Transform (DWT) was used to decompose vehicle vibration signals into Gaussian components as presented by Griffiths [41]. This method exploits the good resolution in time and frequency of the DWT to detect the Gaussian segments in the signal through an iterative process.

As shown at FIG. 4, the first step of this process is to generate a random Gaussian signal based on the PDS of the vibration measured from a vehicle. The DWT is then calculated on both the Gaussian and measured signals. The envelope (maximal and minimal values) of the DWT of the Gaussian signal is used to sequence the vehicle signal; the segments of a signal are considered Gaussian when the DWT of the vehicle signal fits into the envelope. These segments are considered as the first Gaussian component and they are extracted from the signal. Once the extraction is done, a new Gaussian signal is generated from the PDS of the

signal residual and the DWT functions comparison is undertaken again for a predetermined number of times. After all the iterations, the signal residual is considered as the non-Gaussian part of the signal and is fitted with the best Gaussian approximation.

The iterative loop can also be used a second time on each Gaussian component to improve their Gaussian fit. Once the Gaussianity of each component is adequate (based on a kurtosis criterion), a synthetic signal is created using the PDS and time duration of the segments of every component. Despite the fact that the duration distribution of each segment is not taken into account in the proposed algorithm, it is a good method to decompose a non-stationary signal with varying PDS between each segment.

## Bayesian Detector

A statistical-based approach to decompose the Gaussian sequence of vehicle vibration is proposed by Thomas [42] who used Bayesian detector to identify changes in the level and variance and/or autocorrelation between successive measurement series. To ease the identification, a Box-Cox transformation is applied to the vehicle signal to change the measurement scale. An AMOC algorithm [43] is used on the transformed signal as a Bayesian detector to divide the different random process of the signal. This method appears complex, but is well known and widely used in many areas of applied statistics. One drawback of this fast iterative algorithm is its risk of instability. The algorithm also requires several coefficients to be fixed. Further experimentation should be undertaken on this method to provide a significant assessment and guidelines to generalize its use.

# TRANSIENT EVENTS SIMULATION

Anyone who has ever used a road vehicle would agree that the road excitation is not only defined by a series of random excitations but it also contains transient events. These events occur, for instance, when the vehicle travels over potholes, cracks, manholes, speed bumps, railway crossings and so on. Many attempts have been made by researchers to include the transient events in vehicle vibration simulations.

However, as Kipp [5] advocates, this is far from trivial. For instance, simply adding (superimposing) impacts to a random signal has serious limitations. The user has to decide how many impacts and the amplitude to add and how to appropriately distribute them. The various shapes of the impacts also have to be defined taking into account the dynamic behavior of the vehicle (structural modes excited by impact).

Rouillard and Richmond [44] proposed a method to include the dynamic behaviour of vehicles when generating a synthetic impact using the Inverse Fourier Transform of rail vehicles spectrum which was modified with a constant zero degree phase. This transform creates a wave packet similar to impulse vibration response of the vehicle.

Prior to transient event simulation, their detection is also a challenge that needs to be addressed in order to characterize their occurrences in a real signal. The crest factor of the signal is used by many researchers to detect transient events [13, 18, 23, 40, 45-48], which is the ratio between the peak values of the signal and its RMS value $\sigma$,

$$c = \frac{\text{peak}}{\sigma}.$$

(eq. 3)

This method is however highly heuristic because it is based on two subjective criteria: (1) the signal segment length used to calculate the RMS is very important, especially for non-stationary signals and (2) what is the threshold defining a transient event. Bruscella [31] proposed an enhanced method to extract transients based on the moving RMS drop-off distance and the crest factor. When these indicators reach a certain threshold a transient event is detected and the segment containing it is extracted from the signal. However the main shortcoming is that the method remains subjective because the detection is reliable on too many user defined variables.

Lu and Ishikawa [49] also used a highly subjective method to detect transient events with video analysis to validate the transient detection made on the acceleration data of vehicle using Oscope® software (Ono Sokki®). Unfortunately, no further information about the software algorithm is provided. Analysis of truck vertical acceleration data and the same data with the transient events removed using the Oscope® software shows that shocks have more effect on certain vehicle speed and increase the frequency range of the vehicle response [39]. Without giving a precise indication on how the detect transients, this paper highlights the importance to consider the transient and the random broad brand vibration components of a vehicle response separately.

Wavelet decomposition is proposed by Wei, Fwa [50] to detect discontinuities (such as cracks) in road profile data which correspond to transient events on vehicle vibration. To do so, the road profile is decomposed into frequency sub-bands with the Wavelet. According to this study, when a discontinuity occurs in the road profile, some sub-bands are excited more than others which facilitates its detection. However, the method was only tested on discontinuities that were artificially added on road profile measurement. Therefore the frequencies contained within the profile discontinuities are determined by the user and do not necessarily represent reality. Signal sub-bands decomposition could be an accurate method to characterized transient events on vehicle vibration measurements.

## HARMONIC SIMULATION

It is generally accepted that vehicle vibration is mainly composed of random processes (including the random occurrence of transient events) but that does not mean that harmonic (determinist) components are not also present. This specific type of vibration is not induced by the road but by the vehicle itself such as engine or drivetrain-related vibration and unbalanced wheel(s) vibration [51]. While harmonic vibration is well known in railway vehicle vibration [52], to the best knowledge of the author, they are only briefly discussed in term of road vehicle vibration by Charles [17]. It is suggested that Waterfall plots could be used to study vehicle speed dependency to certain vibration, but no application is presented.

## DISCUSSION AND CONCLUSION

Road vehicle vibration simulation methods have been studied for several decades, and even though significant improvements on the earliest simulation methods have been made, the current methods contain some significant limitations. As described in this literature review, it is recognized that the Gaussian PDS-based (standardized), time replication and the non-Gaussian methods are not sufficiently accurate to realistically simulate vehicle vibration because of their statistical limitations and their discrepancy with the real nature of these vibration.

Despite this major shortcoming, the Gaussian PDS-based method remains broadly used today to simulate road vehicle vibration probably because it is recommended by several international standards. This is a proven practice to ensure that the packaging will be effective, but it is far from being the best method for optimisation. Its simplification of the road vehicle vibration generally increases the severity of the excitation. Therefore packages that survive the standardised simulation are more likely to be over-designed.

A good simulation method should reproduce the three modes present in vehicle vibration, i.e. the non-stationary random, transient and harmonic components. So far, a number of effective methods has been proposed to characterize the non-stationarities such as: the Random Gaussian Sequence Decomposition [18], Wavelet Based Gaussian Decomposition [41] and the Bayesian Detector [42]. But no definitive method has been developed and validated to identify and characterize the two other modes of vehicle vibration.

Two elements should therefore be improved to provide more accurate vehicle vibration simulations. First, transient and harmonic signal components must be well characterized, and second, a generalized method including all three modes must be developed.

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