BLIND DOPPLER SHIFT COMPENSATION OF VEHICLE NOISE AND ITS CHARACTERIZATION FOR TRAFFIC NOISE SIMULATION

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Abstract. While a huge amount of literature has been devoted to the study of traffic noise, its aural simulation has received much less attention. Such simulation enables the determination of the sound both outside and inside buildings by means of proper filters. In recent years, a technique based on sound recording of each isolated vehicle in a fixed station, followed by Doppler compensation and noise characterization has been developed. Although this technique takes into account each source more precisely (such as engine and exhaust noise with load effect) as well as aerodynamic noise, it depends on the emission of a pilot tone from the source. This tone allows for the retrieval of the vehicle speed. In this paper, a new Doppler compensation method is proposed, based on the vehicle speed estimation from the tones contained in the recorded signal. This technique may be applied to any vehicle as far as it is reasonably isolated from other vehicles, it does not contaminate the signal of interest, and it needs no pilot tone emission from the source, making the method more practical. For aural simulation, a new model based on a polar scheme is considered and proposed. In this paper, the proposed method is assessed with experimental data, and results are compared with those of other existing techniques.

1 INTRODUCTION

Environmental noise has been and is currently being assessed and legislated in a decibel-reduction paradigm based in limit values for statistical levels such as equivalent noise level (L_{eq}) with corrections based on day period, spectral content, impulsiveness, tonality, etc. (EU Directive 2002/49/EC, 2002; ISO 1996-1, 2003, Ley 1540 Bs As, 2005).

Currently developing paradigms on noise assessment (Accolti and Miyara, 2010; Accolti et al., 2010) are incorporating other cues of environmental sound such as semantic content, loudness, sharpness, roughness, heritage and cultural backgrounds based on perception, psychological and sociological factors. Although these paradigms are currently being developed and many branches are found in the topic, a common requirement in all these branches is the auralization of Soundscapes. The auralization can be based in sound recordings but only when the site already exists. In cases when the site does not exist (e.g. projects, or when subjectively assessing the effects of different factors in a Soundscape) the sound synthesis and aural rendering is also a requirement.

Aural rendering is a wide topic that includes many applications such as architectural acoustics design, computational games and immersive reality. This article focuses in the immersive reality branch with high applicability in environmental noise assessment but the methods and results are of interest for other applications as well.

Audio rendering for fixed sound sources in virtual immersive reality is somewhat easy than moving sources. In the case of fixed sources the render can be computed using digital filters techniques as in Perea-Pérez et al., 2010 or directly using frequency sampling for estimating the attenuations of air, geometric divergence, barriers, objects, ground, etc. described in well known methods for sound propagation calculation (e.g. ISO 9613-2, 1996). These methods assume point sources neglecting any polar pattern effect and barriers and object reflection temporal effects.

In the case of moving sources, such as road vehicles, the filters used for fixed sources should be updated each instant and the Doppler shift should be incorporated. Furthermore the source should be previously characterized and for that purpose the directivity of the source must be accounted.

In this article car passbys are analyzed to characterize the source. Similar characterizations have already been conducted in Marengo-Rodriguez and Miyara, 2009 and Marengo-Rodriguez et al., 2010. The first step is compensating the Doppler shift using an estimated car velocity. The estimation of car velocity in those cases was made using devices previously located in the car, in the first case a sound source emitting a pilot tone and in the second case a mechanical counter based on a system composed by a reed switch and a magnet attached to the rear wheel. In this article the car velocity is directly estimated, as an average number, by analyzing the tonal components of the car motor. This article also introduces the source characterization by an audio emission polar pattern of the sound source. This characterization permits synthesizing different instants of a car passby for any source-receiver configuration in a similar vertical direction. Wideband polar patterns include one value for each direction ϑ, third octave band polar patterns include thirty one values for each direction and finally an audio polar pattern includes $F_s \times t$ samples of an audio signal of t seconds long sampled at sampling rate of F_s samples/second for each direction. Of course the length of t depends on the velocity of the assessed car and how the polar pattern is discretized.

The next section is Doppler compensation where the problem is solved using direct measurements of instantaneous car velocity and an average estimation by analyzing the Doppler shift in a tonal part of the noise emitted by the car (i.e. motor noise). The following

sections are audio characterization as a polar pattern and the concluding remarks.

2 DOPPLER COMPENSATION

As was reported in Marengo-Rodriguez and Miyara, 2009 and Marengo-Rodriguez et al., 2010 the sound source under study has both wideband noise and multitonal components. However, in order to characterize the source, the sound recorded at the fix-positioned station must be free from Doppler shift and geometric divergence. Doppler shift can be compensated by determination of the distortion of a test tone emitted from the source. In other words, the test tone of frequency f_0 is recorded at uniform time intervals $t = 0, t_1, 2\,t_1, \ldots, n\,t_1$ as

$$f_D(t) = f_0\,c\,/\,[c + v_\beta(t)], \tag{1}$$

where c is the sound speed and $v_\beta(t)$ is the radial component of the instantaneous speed of the source with respect to the receiver.

2.1 Indirect method

The indirect method relies on the analysis of a test tone artificially emitted from the source, where the phase produced by the distorted frequency $\phi(t) = 2\pi \sum f_D(t)$ is matched to the phase produced by the undistorted tone at nonuniform time intervals $\Delta t' = t_1 + \Delta t_1, t_1 + \Delta t_2, \ldots, t_1 + \Delta t_n$ [i.e., $\phi(t') = 2\pi f_0 \sum \Delta t'$]. This technique proved to be very efficient, even for low signal-to-noise ratios, since the compensated sound contained the test tone with frequency variations perceptually null.

Since the aim is to aurally simulate moving sound sources effectively, our focus is to compensate frequency distortions that are perceptually relevant. To this aim, it is important to note if both wideband noise and multitonal components are perceptually distorted by Doppler shift. Since we are studying vehicle noise for urban conditions, its velocity is low and phase distortion is relevant only for tonal components of the source noise. Wideband noise is not perceptually affected by Doppler shift. By looking at Eq. (1), it is easy to see that the higher the frequency of the tone from the source, the stronger the frequency distortion and the more perceptive is such distortion. Therefore, it is important to detect the presence of tonal components and their mean frequency in order to apply the correct Doppler shift compensation technique. If such frequencies are low, Doppler shift must be compensated but the method applied for its application is not critical for perceptual purposes. In order to illustrate the sound recorded from a passby, Figure 1 displays the spectrogram corresponding to the Ford Falcon in an open profile street, where the average vehicle speed was about 20 km/h and the minimum distance between the source and the recording station was $R = 2.1$ m. The time interval adopted was two seconds long around the instant corresponding to the minimum distance between source and receiver (also referred to as *reference instant*). More details concerning this signal are reported in Marengo-Rodriguez et al., 2010. Tonal components are concentrated at frequencies below 200 Hz, as shows the amplitude spectrum in Figure 2.

The direct method was introduced somewhere else (Marengo-Rodriguez et al., 2010) but is briefly described here to compare results with the method introduced herein (i.e. blind method).

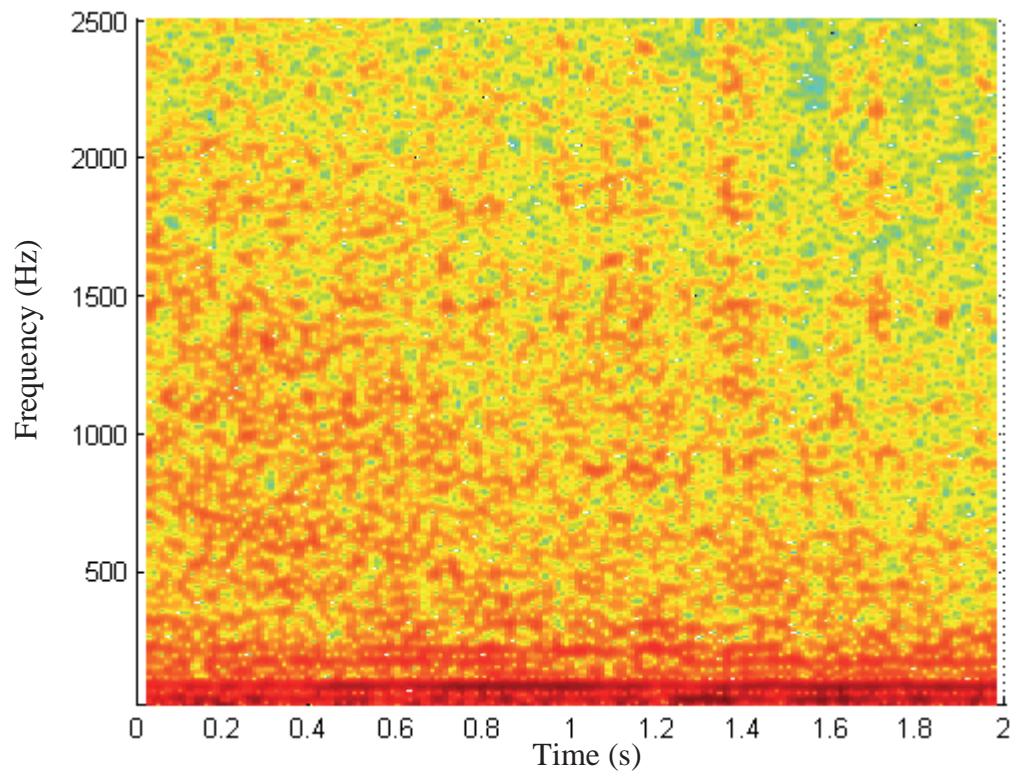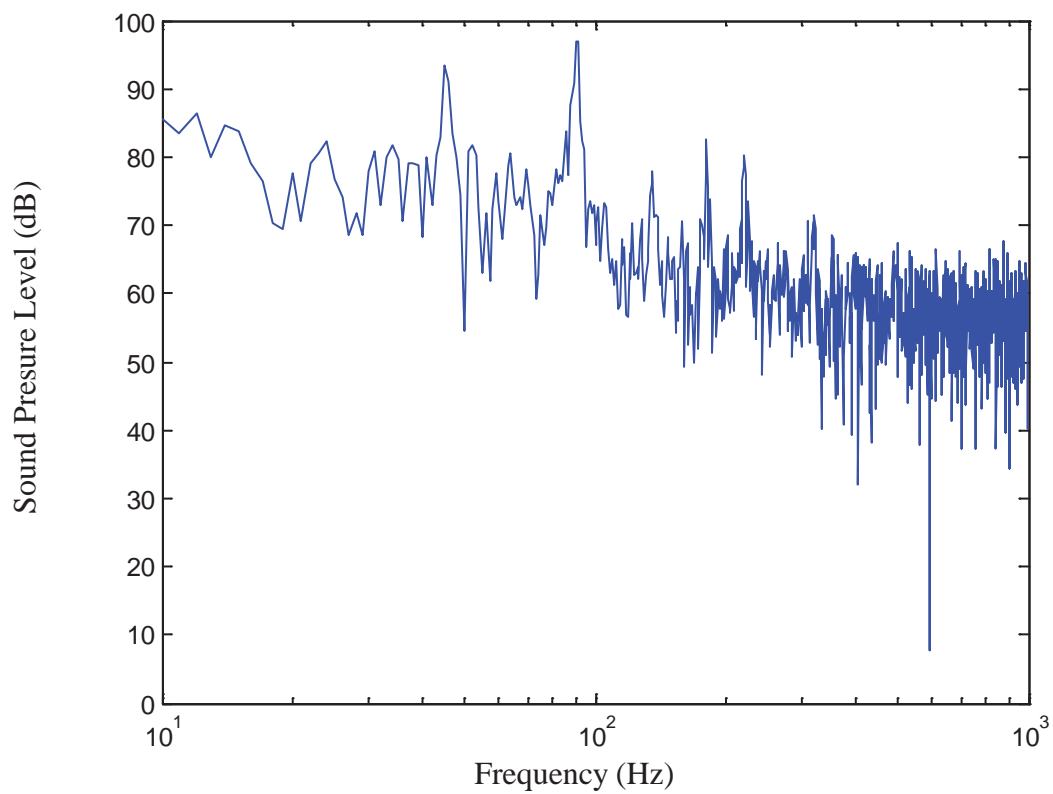Figure 1: Ford Falcon passby spectrogram.

Figure 2: Ford Falcon passby amplitude spectrum.

2.2 Direct method

This method consists in a mechanical counter similar to those installed in bicycles, i.e., a magnet attached to the rear wheel activates a reed switch attached to the vehicle every time the wheel completes one revolution. The resulting set of pulses (recorded in a sound meter) encodes the vehicle speed. This method proved to be more efficient than the indirect method (i.e., the one based on the test tone), since it is not affected by low signal-to-noise ratios and allows to measure local speed variations due to accelerations of the vehicle under study. It is important to remark that the discrepancy between this method and the indirect one is small, about 5 %.

With the direct method it was possible to detect correlations between tonal components of the source noise and the mechanical system composed by: the motor, the gearbox and every device associated with it (such as exhaust). Such correlation exists since the frequency of such tones is modified at the same time local accelerations of the vehicle are detected. Therefore, if the recorded sound contains pseudotones with slightly varying frequencies, it is very probable that the vehicle is accelerating.

2.3 Blind method

The blind method is inspired in a technique developed for aircraft noise, using tonal components of propeller or turbine depending on the propulsion method (Yanitelli et al., 2001). It is also similar to the indirect method mentioned in a previous section but in this case none instrument should previously be incorporated to the vehicle.

The blind technique consists in detecting the evolution of the instantaneous frequency of the tones emitted by the source. In case the time interval analyzed is sufficiently short and the vehicle is not accelerating, its speed remains constant. Therefore, the frequency f_0 of each tonal component of the vehicle motor is expected to be constant and Eq. (1) verifies. In order to detect such tonal frequencies, the input spectrogram is determined and consecutive local maxima are detected with an adequate ridge searching algorithm (Marengo-Rodriguez and Miyara, 2009). Then, the detected sequence is fitted (in the least square sense) to the theoretical expression displayed in Eq. (1). In this step, the frequency f_0 is adopted as input, and both the average speed v_β and the Doppler shifted frequency f_D are estimated.

The input spectrogram along with the instantaneous frequency corresponding to the most relevant tones are illustrated in Figure 3. It corresponds to the same signal referred in Figure 1. In this spectrogram, local consecutive maxima are searched around the frequencies corresponding to the most intense tones. This information is detected automatically from the amplitude spectrum shown in Figure 2. The least squares fit to these sequences have minimum error for the harmonic corresponding to 45 Hz and is illustrated in Figure 4. The estimated average speed is 17.43 km/h, which differs from the average speed detected with the direct method (shown in Figure 5) in 13.37 %.

The Doppler shift, as well as the geometric divergence, is successfully compensated with the blind method, since frequencies variations corresponding to tonal components are highly reduced, and the signal envelope is also smoothed. Figure 6 illustrates the spectrogram corresponding to the input and compensated signals with both the blind method and the direct technique for comparison purposes. In order to assess the effectiveness of the proposed method, the graphic is displayed around the frequency of the test tone added from the vehicle, which does not depend on the motor such as other tonal components emitted from the source.
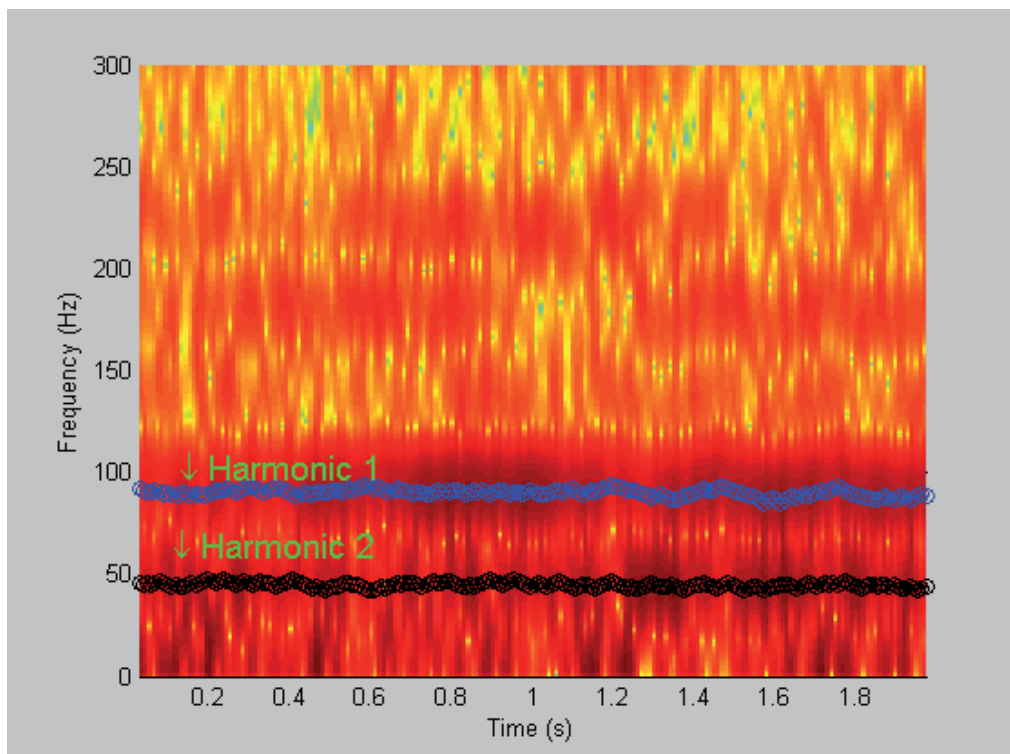
Figure 3: Passby spectrogram and the instantaneous frequencies corresponding to the most intense tones.
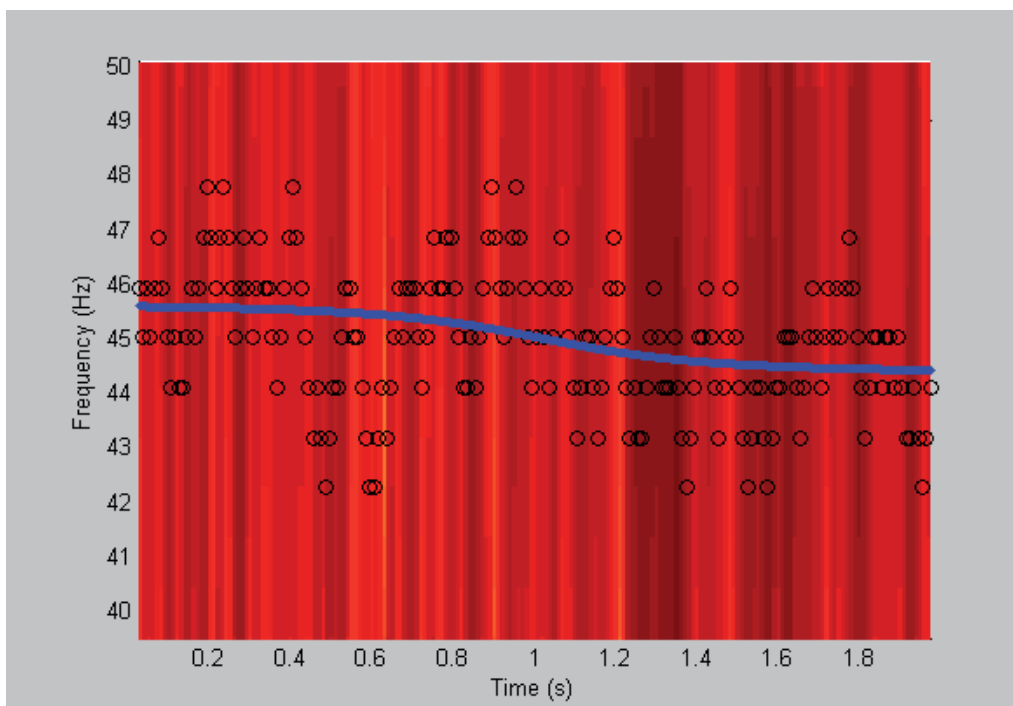

Figure 4: Instantaneous frequency for a particular vehicle tone and its least square fit according to the theoretical Doppler shift equation.
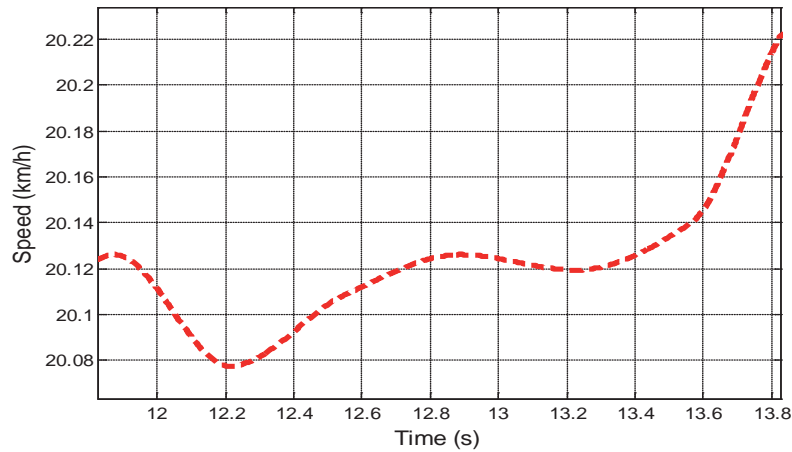
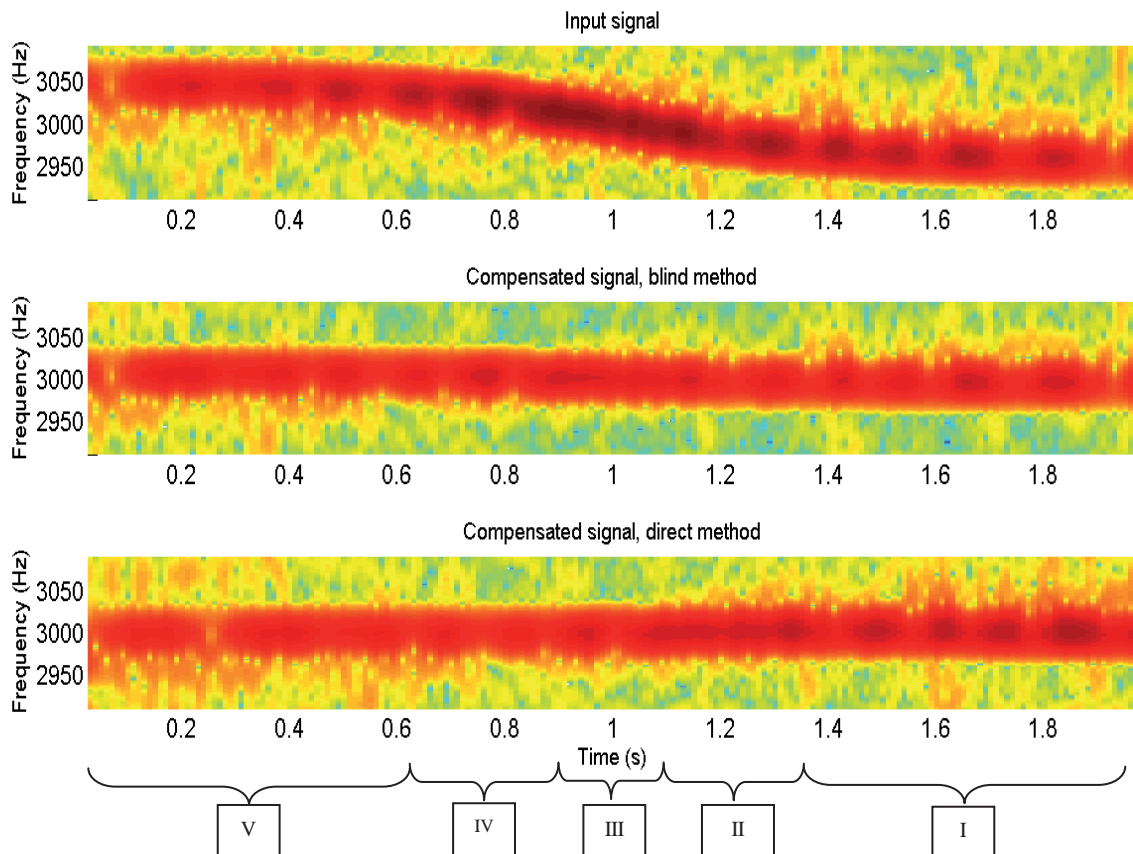Figure 5: Instantaneous vehicle speed measured using the direct method.

Figure 6: Spectrograms around the test tone added from the source, corresponding to the input and compensated signals using the blind method and the direct technique for comparison purposes.

3 AUDIO CHARACTERIZATION

The sound source was treated as a point source, and the compensated signal was divided into a few time intervals as shown at the bottom of Figure 6. Each of these intervals is associated with a 30 degrees-wide angle interval in the polar scheme and labeled with Roman

numerals (see also Figure 7). For the analyzed time interval and the vehicle speed determined with the direct method, the corresponding angle intervals for the polar scheme started in 24.01 degrees and ended in 180-22.95 = 157.05 degrees. In case the blind method is used, the angle error is always less than 6.3 degrees and 3.6 degrees on average.
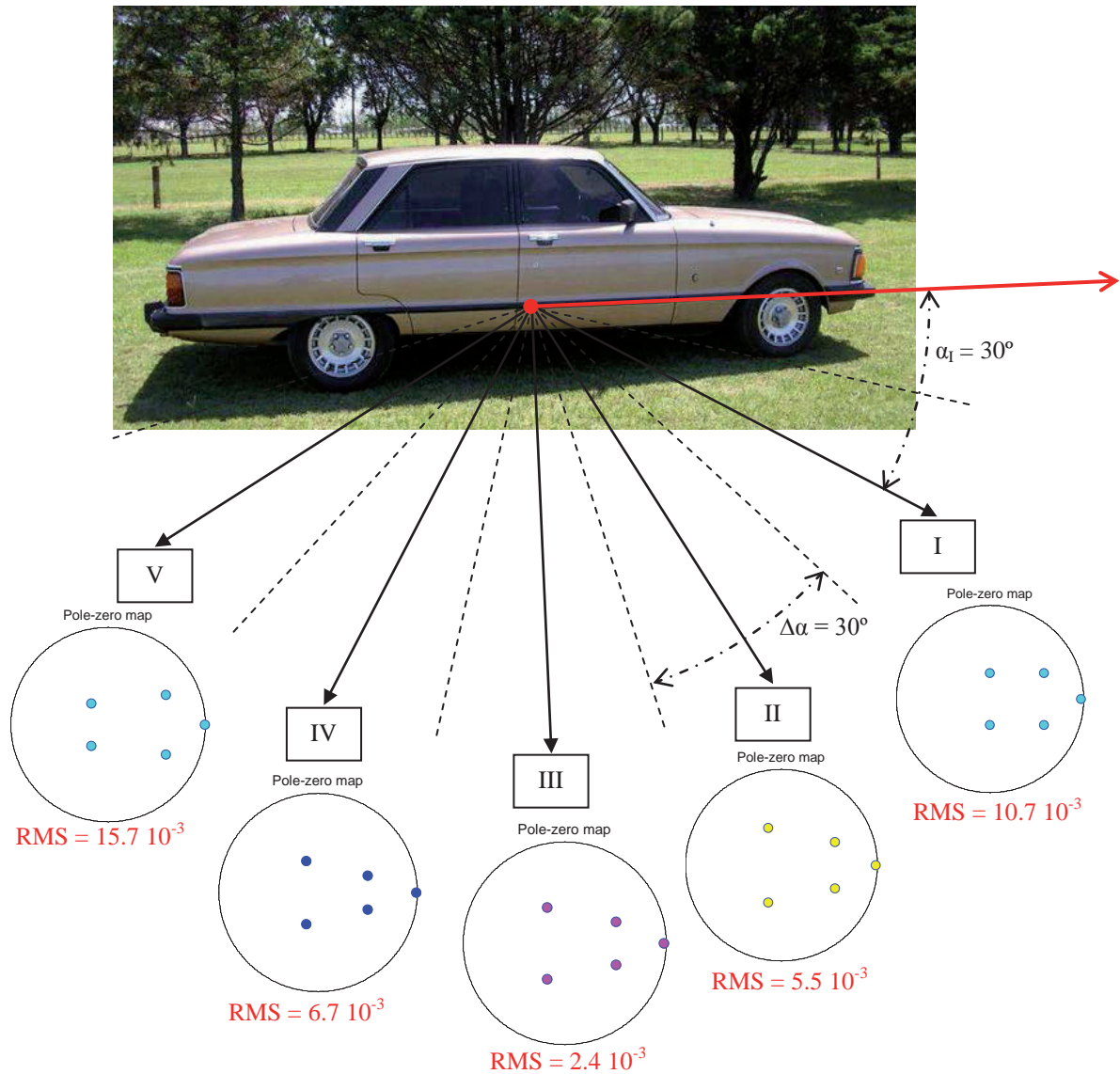

Figure 7: Polar scheme for audio characterization of a road vehicle, and associated parameters corresponding to the wideband component of the source noise.

For each angle interval, the compensated sound is decomposed into tonal information and wideband noise. Tones are detected by means of a ridge searching algorithm applied to the spectrogram of the compensated signal (see Figure 8). For this case, the frequency resolution adopted was higher than for the recorded signal, since it was not necessary to detect temporal changes in the frequency of the tones (contrary to what was necessary for detecting Doppler shift).
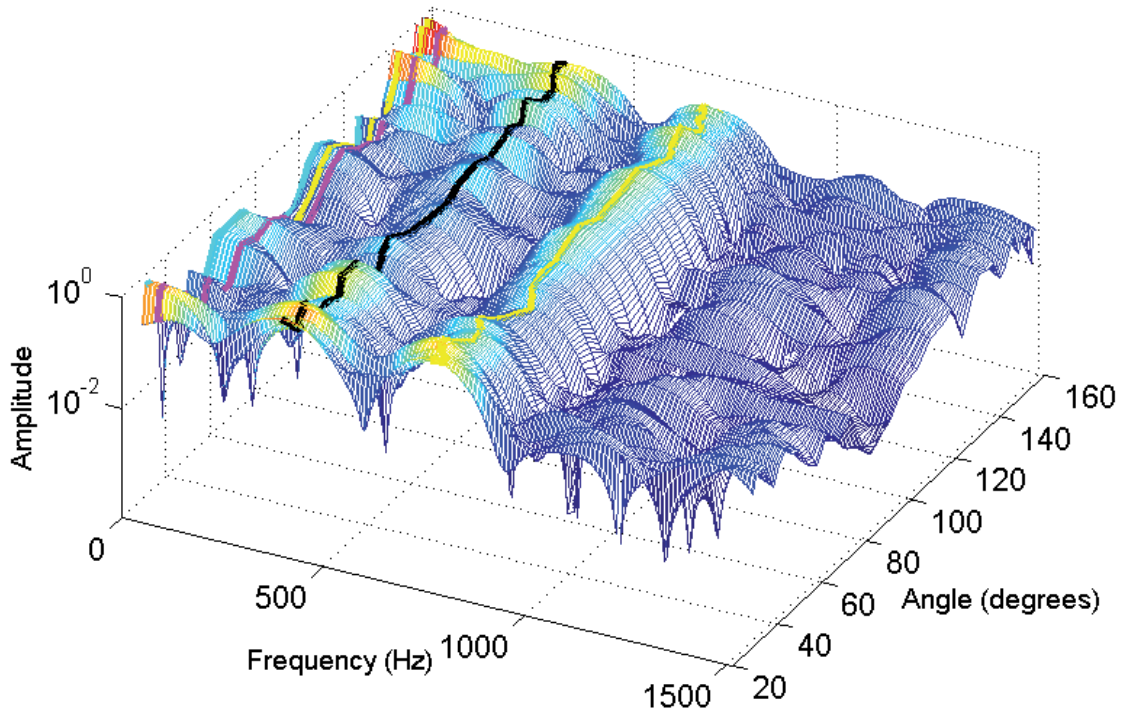
Figure 8: Spectrogram of the compensated signal and detected tones using the ridge searching algorithm.

The frequencies estimated from the spectrogram of Figure 8 change smoothly with time as illustrates Figure 9. This is an expected result, since the experiment was carried out in order to keep speed as constant as possible during the time interval analyzed. There is also a relationship between the estimated frequencies, such that harmonics of order 1, 4, 6, 33 and 66 are detected.
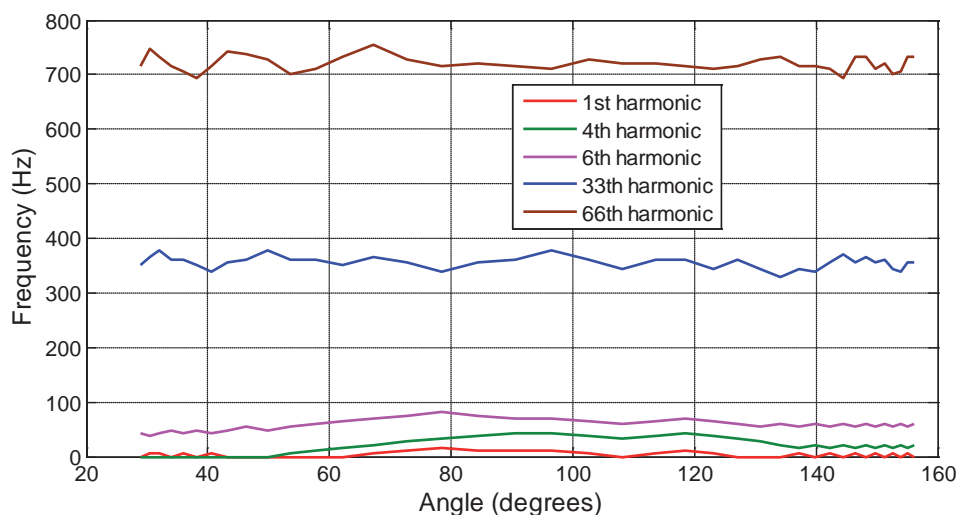

Figure 9: Temporal evolution of the frequencies detected in the compensated sound. The relationship between the mean frequencies of each pseudotone is displayed in the legends.

The RMS (root mean square) value was determined for each component, and the mean frequency was also estimated for each pseudotone (see Table 1). For the present study, these

pseudotones are illustrated in Figure 10, and they concentrate a high percentage of the input energy. This is valid especially for harmonics number 1, 4 and 6 (see Figure 11, top panel). The remaining pseudotones are quite less intense but psychoacoustically relevant. The multitonal component and the wideband noise are graphically represented in Figure 11.

	Input	Wideband noise	Harmonic (tonal component)					
			# 1	# 4	# 6	# 33	# 66	All
RMS $\times 10^3$	15.4	7.6	0.38	0.4	1.5	0.1	0.08	2.8
Mean frequency (Hz)	-	-	10.8	43.1	70	360	716	-

Table 1: Parameters corresponding to the input compensated signal and its associated components.
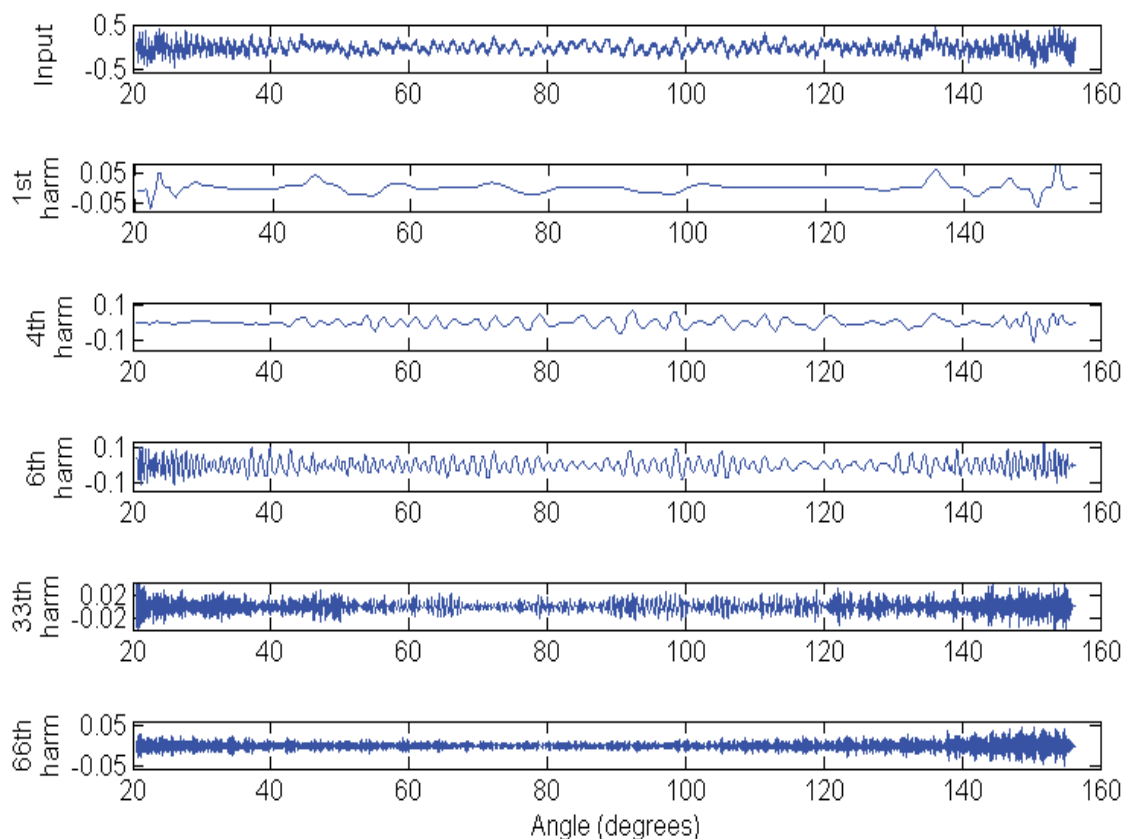

Figure 10: Input compensated signal and the corresponding tones detected.

How is the wideband component characterized? It is represented as white noise filtered by an N-th order Linear Prediction Coefficients (LPC) filter (Marengo-Rodriguez and Miyara, 2009). By choosing $N = 5$ for each angle interval, the resulting corresponding pole-zero diagrams are those graphically displayed at the bottom of Figure 7. The RMS values corresponding to each angle interval are also mentioned below the previously mentioned pole-zero diagrams. It is very interesting to note that all these diagrams are very similar to each other, which is expected since the spectrum of the wideband component is not much affected by the time interval analyzed. Such spectrum is displayed in Figure 12.

Input signal and 1st+2nd+3rd harmonics

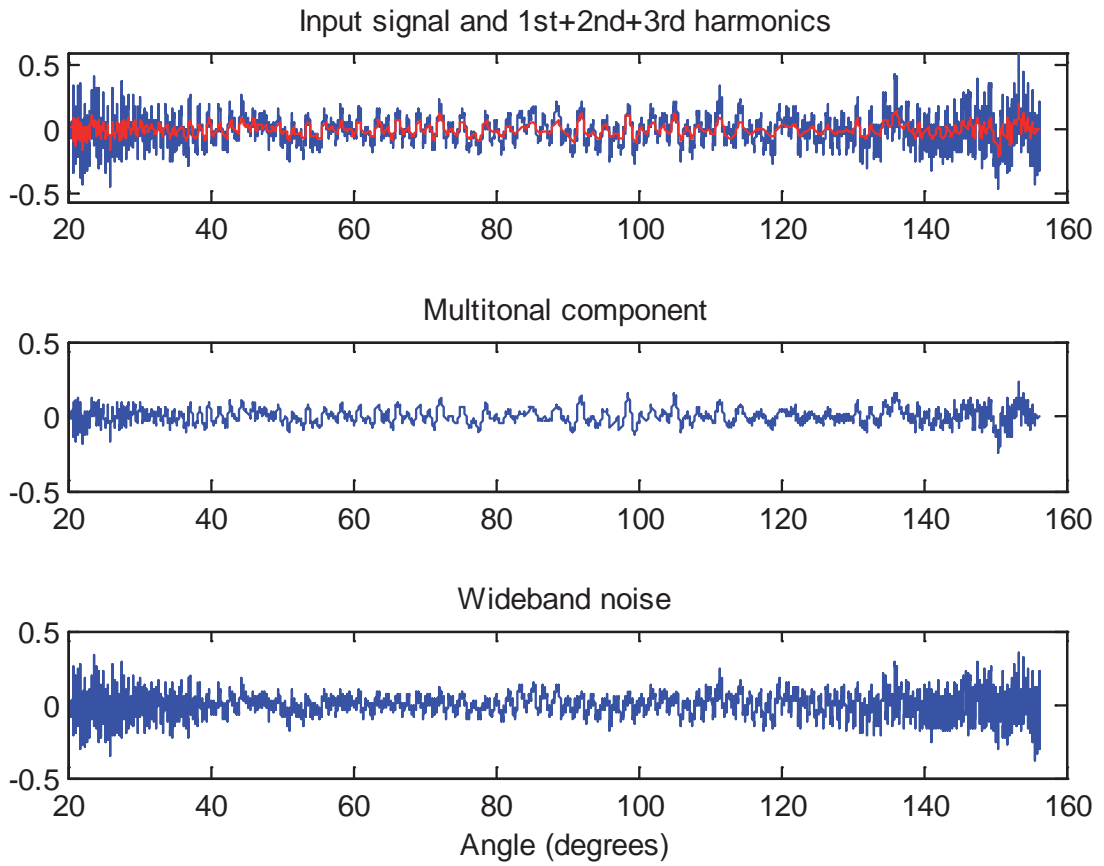### Multitonal component

Wideband noise

Figure 11: Input, multitonal component and wideband noise. The sum of the first three pseudotones is also displayed at the top of the figure.
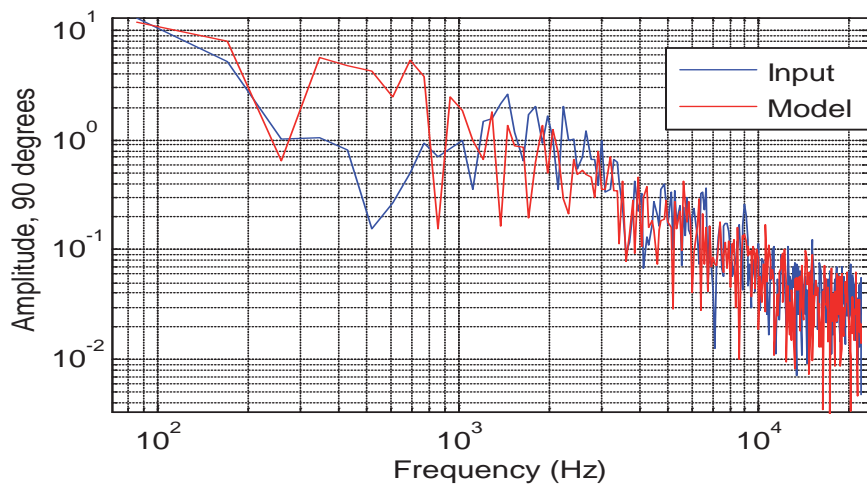
Figure 12: Spectrum of the input and the simulated wideband component corresponding to the central interval (from 75 to 105 degrees).

In order to aurally simulate the wideband noise for *any* angle in the interval analyzed, the

following method is proposed. For each interval I, II, III, IV and V, the amplitude spectrum of the simulated wideband noise is determined. Then, these spectra are interpolated with each other using cubic splines. The result is a wideband noise very similar to the input one (except for tonal components), as illustrated in Figure 13.
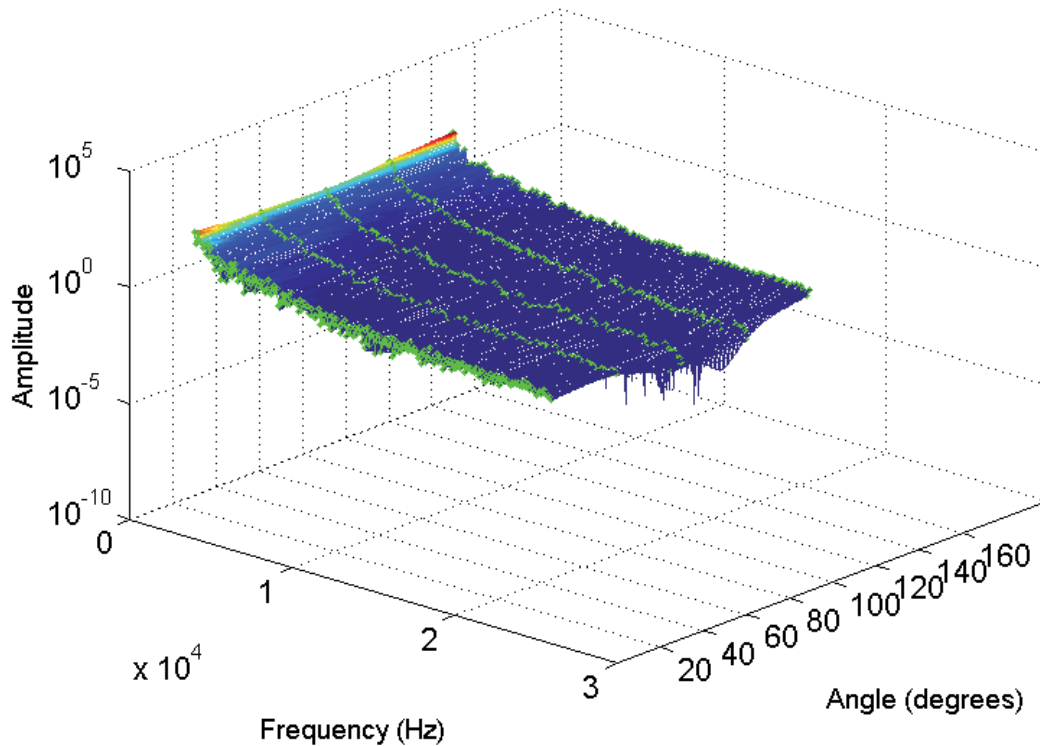

Figure 13: Spectrogram corresponding to the interpolation of a few amplitude spectrum data (green curves). These spectra correspond to the LPC-simulated wideband noise corresponding to the angle intervals I, II, III, IV and V of the polar scheme.

4   CONCLUSIONS

A new method for compensating Doppler shift was introduced and successfully applied for studying vehicle noise and it associated components. Although the proposed technique is less effective than other methods, it proved to be efficient for estimating the mean speed of the moving source with moderate error. This method was applied to experimental data and it aims to compensate Doppler shift for many other types of vehicles, without the need to introduce any additional hardware.

In order to characterize vehicle noise, a polar scheme consisting of a few angle intervals was proposed and studied. Both multitonal and wideband components were successfully extracted, and a relationship between the LPC models was found for the wideband noise. This result allows to characterize the sound source for any angle in the analyzed interval.

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