***inter.noise 2000***
***The 29th International Congress and Exhibition on Noise Control Engineering***
***27-30 August 2000, Nice, FRANCE***

**I-INCE Classification:** 7.2

# THE FOCUSSED VERTICAL ARRAY FOR THE DESCRIPTION OF THE NOISE SOURCES ON A MOVING CAR

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**Keywords:**
MICROPHONE ARRAY, VEHICLE NOISE, BEAMFORMING, NOISE SOURCE

## ABSTRACT

Knowledge of the height of sources concerns vehicle description as input parameter for traffic noise prediction models and design of noise barriers. The beamformed array has become a common measurement device for locating noise sources on vehicles. It is pointed out how measuring over reflecting road surface may disturb the interpretation of beamforming results. A passenger car is studied over a wide range of driving conditions (speed, gear, engine rpm). The main part of noise is coming from an area located under the car chassis. It includes rolling noise and mechanical noise, whose relative weight depends on speed and gear. A second weaker source is located near the upper part of the front wheel, and cannot be attributed to the motor noise only.

## 1 - INTRODUCTION

Among the various needs for vehicle acoustic description are the global understanding of its noise components in connection with the mechanical parts location (for instance needed by the manufacturer confronted with noise regulation) [1], or the more general knowledge of the noise sources in a vehicle class as inputs for models involved in far-field prediction or in design of noise reduction devices (noise barriers) [2]. Microphone array techniques have become common measurement solutions for noise source identification. Even if they are all based on a set of microphones, distributed over space according to a predefined optimum layout, they may involve however different processing grounds [3], [4], [5]. Among them is a class of methods taking advantage of the spatial coherence of the sound field over the array to synthetically build a directional measurement device, whose beam direction may be moved by calculations. They consist of compensating differences between propagation delays (and sometimes between attenuations) to reinforce signals impinging from a given direction while attenuating signals from other directions. One subclass operates on cross-correlations between microphones (interferometry) [6], whereas another subclass involves direct signal recombination (beamforming) [4].

The performance of far-field traffic noise prediction models is directly affected by the acoustic description of the moving vehicle. Similarly the design of noise barriers is based on the heights of the vehicle sources, the cost and the efficiency of the device depends strongly on how accurate these heights are known. In many cases the vehicle is represented by an equivalent point source [7], [8]. The source height can be determined by fitting calculated results, using an acoustic propagation model, to measurements performed at several heights [8] or several distances [7]. Microphone arrays may provide an efficient way of evaluating the vertical position and strength of sources, without any assumption on their number [2], [9]. For this, a vertical linear array is sufficient. In a previous study, we investigated the vertical sources location corresponding to mechanical noise sources only, by measuring a passenger car at a stanstill for various engine rpm [9]. The major noise part was proved to come from the underbody of the vehicle. The present study concerns the vertical sources location of a moving passenger car for various speed, engine rpm and gear conditions.

Part 2 will briefly recall beamforming and dedopplerization for moving sources and part 3 will describe the experimental procedure. When measuring over reflecting ground, a coherent image source is associated to each actual source. Though impinging the array with a different incidence angle, the image source may disturb source location (part 4). After identifying the main sources (part 5), the influence of the driving conditions on the sources strength will be considered to point out the individual contribution of rolling noise and mechanical noise.

## 2 - ARRAY PROCESSING: BEAMFORMING AND DEDOPPLERIZATION

Consider a set of $p$ microphones arranged along a line and separated by a distance $d$. This array may be focussed on any point $F$ of the space in order to detect there a possible source. The beamformed array compensates for the propagation delays so as to put in phase the individual microphone signals for a source $S$ supposed to be at the focus point $F$. If the source-microphone distances are very different over the array, it may be advantageous to compensate also for the propagation attenuations:

$$y\left(F,t\right)=\frac{1}{p}\sum_{i=1}^{p}w_i\frac{r_{iF}}{r_{ref}}p_i\left(t+\frac{r_{iF}-r_{ref}}{c}\right) \tag{1}$$

where $p_i(t)$ is the sound pressure on microphone $i$, $r_{iF}$ is the distance between the focus point $F$ and microphone $i$, and $r_{ref}$ is the distance from the focus point to some reference point (for example the array centre). $c$ is the celerity of sound. $w_i$ is a shading coefficient.

The mean power at the output of the array, estimated by the time integral $\frac{1}{T}\int_0^T y\left(F,t\right)^2 dt$, gives then the power of the source located at point $F$, like it would be measured by a microphone located at the reference point. Signals coming from sources outside the focus point tend to cancel. The directional characteristics have already been widely studied [4]. The main point is that a given array may be used on a restricted frequency band, defined on one end by microphone spacing (spatial aliasing) and on the other end by the array length $p.d$. The processing described by (1) may be used directly for wideband signals, for example in octave or third octave bands.

In the case of a moving source, large variations of frequency may occur on the different microphones during the pass-by, thus disturbing the recombination of signals. The solution consists of moving the focus point together with the object during the time interval $T$. This forms dedopplerization. For an object moving horizontally in front of a vertical array, the Doppler coefficient differs little from one sensor to the other so that for a rough analysis, dedopplerization could be ignored.

## 3 - MEASUREMENT SET-UP AND PROCESSING

The vertical array was located on the track side. It was composed of $p$=15 microphones. The microphone spacing was adapted to the frequency bandwidth: $d$=30 cm for the frequency range 500 Hz − 1000 Hz, $d$=15 cm for the frequency range 1000 Hz − 2000 Hz. Since the main sources were expected to be near the ground, the array has been inclined so that its normal pointed toward the main source area (Fig. 1). This was motivated by the resolution of the array being best around its normal.

The vehicle was a Citroen ZX estate equipped with a diesel engine. It run at a constant speed on a concrete asphalt test track, at a measurement distance (between the nearest side of the car and the plumb of the array centre) of about 2.55 m for the lower frequency range and 1.9 m for the upper frequency range. The driving speed was determined by the choice of the gear (1 to 5) and the engine speed (1000 to 3000 rpm). Thus the speed ranged from 13 km/h to 110 km/h.

Microphone signals have been dedopplerized, and shaded to increase the spatial dynamic of the device. Time integration was fixed to $T$=60 ms. The focus point has been moved vertically with a step of 10 cm. Theoretically the vertical array is unable to locate sources in the horizontal direction. However if a source has a strong horizontal directional characteristic it could be located nevertheless. For this reason the vertical focussing operation has been calculated again each time the vehicle moved ahead by 10 cm.

## 4 - INFLUENCE OF THE COHERENT IMAGE SOURCE

In the presence of reflecting ground, each actual source on the vehicle has an image located symmetrically below the ground surface. Both the source and its image are coherent, and have their own propagation distances to the array. When impinging on the array both signals interfere and the actual source cannot be correctly located: an underlying hypothesis of beamforming actually sets that the sources should be uncorrelated. The effect of the coherent image source has been studied, as a function of the source height and of the frequency. It may be pointed out that in most frequency bands, the location of low height sources is affected, either by resulting in a unique maximum located between the source and its image, or if both separated, by some bias on the source height estimate (Fig. 2). Thus, the detection of a maximum under 20 cm (corresponding to the height of the car underbody) in third octave bands from 630 Hz to 2000 Hz proves that a source is present in the range 0 − 20 cm, but its actual height cannot

**Figure 1:** Measurement set-up for the frequency range 1000 Hz − 2000 Hz.

be determined. This range should be taken as 0 − 30 cm in the third octave 500 Hz. Above these limits sources are correctly located.

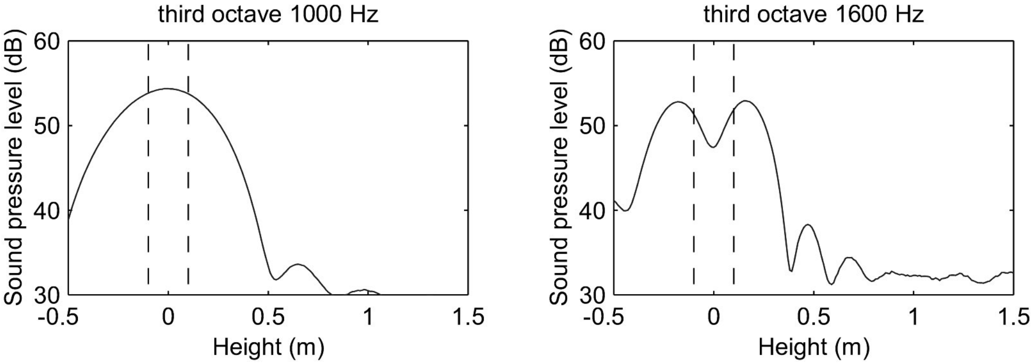

**Figure 2:** Output of the beamformed array for a wideband source at 10 cm (correlated image source at - 10 cm) over reflecting ground; third octave 1000 Hz and 1600 Hz; p=15 − d=15 cm − measurement distance 1.9 m.

## 5 - EXPERIMENTAL RESULTS

Cartographies of the sound pressure level at the output of the beamformed array have been drawn for each vehicle pass-by. The obvious outcome is that most of the sound energy comes from an area very close to the ground, in each frequency band and for each driving condition (Figs. 3 and 4). The horizontal distribution of the corresponding sound pressure level over the whole vehicle pass-by indicates that several low height sources may be spread over the length of the vehicle, with a wide horizontal directional characteristic. As indicated in part 4, the exact height cannot be precisely stated, but it is undoubtedly located under the chassis. It probably includes rolling noise from both wheels together with mechanical noise, which was proved in [9] to come mainly from the car underbody. The mean pressure level on the vertical focus line, calculated from the nose to the rear end of the car, indicates that the vehicle could be vertically represented by a unique source located very close to the ground (Figs. 3 and 4).

The sound pressure level of this main source, taken as the maximum mean level during the vehicle pass-by, has been studied as a function of speed, gear, engine rpm and frequency. From [10], it can be stated that, when sound pressure level at a given speed is observed to be independent of the gear then rolling noise is predominant, whereas sound pressure level is mainly due to motor noise when it does not depend on the gear at a given engine rpm. Fig. 5 represents the maximum of the main source level as a function

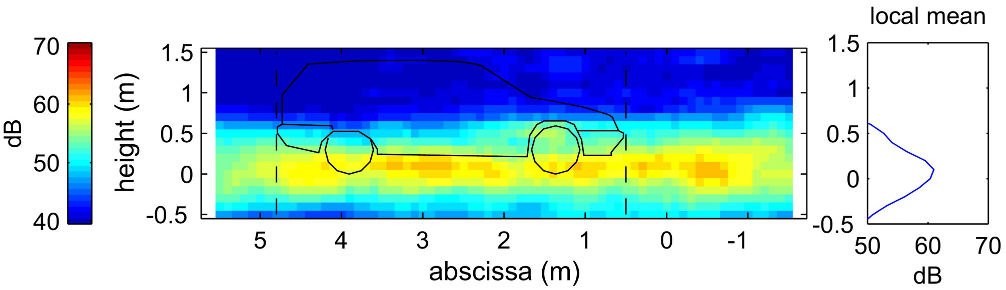

**Figure 3:** Sound pressure level at the output of the beamformed array during the vehicle pass-by (left: cartography – right: mean level between the dashed lines) 25 km/h – 1st gear – 3090 rpm – third octave 2000 Hz.

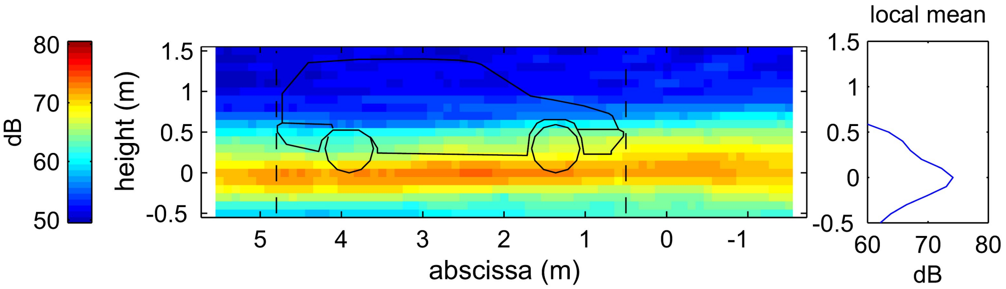

**Figure 4:** Idem Fig. 3 – 112 km/h – 5th gear – 2890 rpm – third octave 2000 Hz.

of speed (left) and of the engine rpm (right) in the third octave 2000 Hz. It shows that at 4 th and 5th gear, as well as above 50 km/h at 3rd gear, noise is mainly rolling noise. Below 25 km/h (1st and 2 nd gear), mechanical noise is predominant. Intermediate driving conditions involve both contributions. The same comments are also valid at 1600 Hz. In the 1250 Hz and 1000 Hz rolling noise is dominant from 3rd to 5th gear, but mechanical noise alone cannot be noticed. At lower frequencies both components are simultaneously present. More details can be found in [11].

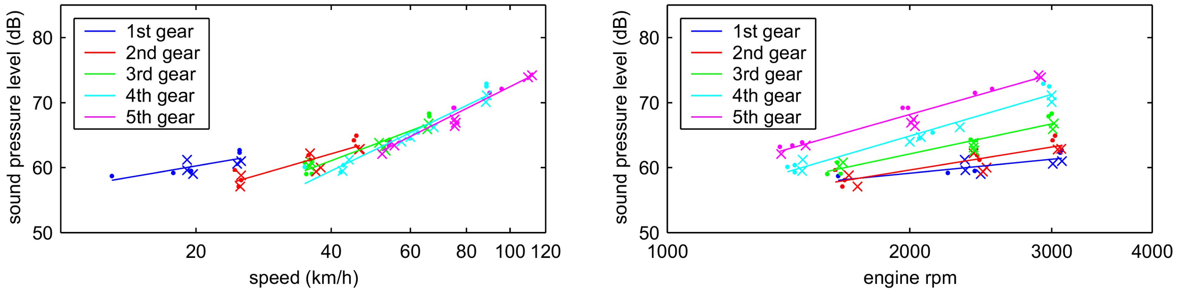

**Figure 5:** Sound power level of the low height sound source in the third octave 2000 Hz.

A second source can be noticed at the upper part of the front wheel of the car (0.35 m or 0.45 m). It is horizontally limited on cartographies, probably due to high directivity. This source had already been noticed when mechanical sources were studied on the vehicle at a stanstill [9]. Even if it cannot always be observed on the colour pictures, in particular when the array resolution is poor, its presence is revealed on the mean levels calculated during the time where the front wheel faces the array, in every driving condition and frequency band (Fig. 6).

In order to study this weaker source, a two-source model has been fit to the mean pressure level. Only cases where the source estimates led to satisfactory global pressure level reconstruction were retained (for instance it matched poorly in the bands 1250 Hz and 1600 Hz). The sound pressure level of the secondary source could then be analysed. On average it is 7 dB weaker than the main source. Contrary to expectations mechanical noise did not appear to be predominant and rolling noise seemed to contribute in all cases. At that point it could not be stated whether the main powerful source influenced the weaker

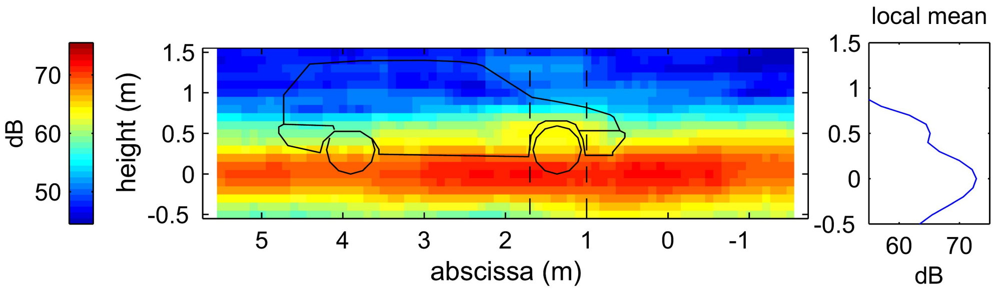

**Figure 6:** Cartography of sound power level and mean level on the front wheel pass-by; speed 75 km/h – 5th gear – 2030 rpm – third octave 1000 Hz.

source estimates or if only physical parameters were involved.

## 6 - CONCLUSIONS

When measuring over reflecting road surface, the performance of the beamformed array may be reduced for sources close to the ground. In the present study configuration the height limit for correct location could be fixed around 20 cm for the most frequency range. The vertical scanning of a moving passenger car over a wide range of driving conditions pointed out that most part of noise originated in the area under the vehicle chassis. This agrees with conclusions drawn by another study based only on acoustic propagation models [12]. The relative part of rolling noise and mechanical noise have been examined. A second weaker source, identified previously as a mechanical noise source on the non-moving vehicle, has also been detected, but a part of rolling noise seems to be superimposed to motor noise.

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