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Energy Procedia 82 (2015) 1017 – 1023

Energy Procedia

ATI 2015 - 70th Conference of the ATI Engineering Association

A review of experimental techniques for NVH analysis on a commercial vehicle

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Abstract

Noise and vibration of automotive vehicles are an increasingly important issue in the automobile industry, for implications on both environmental noise pollution and comfort perceived by driver and passengers. Since noise and vibration performances affect the overall image of a vehicle, they are now considered important factors in the entire vehicle design process. In this regard, an accurate experimental evaluation of vehicle noise and vibration levels in both stationary conditions and urban driving conditions are often necessary for undertaking a refinement process of vehicle sound quality, satisfying the development targets. This paper provides a review of the main experimental techniques adopted for the measurement and analysis of noise and vibration in a commercial vehicle. In order to monitor sound generation in terms of both air-borne and structure-borne noise, the source, transfer path and receiver have to be investigated by noise measurement. For this purpose, different techniques can be employed. Some of them make use of instrumentation (i.e. condenser microphone, sound level meter, sound intensity probe, acoustic holography) which requires particular measurement environments, as it ensures sufficient measuring accuracy only in free field or anechoic conditions. On the contrary, the more innovative pressure-velocity sound intensity method can be used for in-situ tests, without the need to create acoustically treated environments. At the same time, vibration measurements by using proper transducers allow to minimize the structure-borne vibration transmitted from vehicle power plant to chassis and body structure. Experimental modal analysis is another standard tool in vehicle NVH development for determining the dynamic characteristics of a system, and therefore for reducing the risk of failure or excessively high structural vibration or sound pressure levels.
Hence, in present work, noise and vibration frequency spectra of experimentally analyzed case studies are given, to illustrate how accurate experimental tests are fundamental for identifying the generation causes of typical noise and vibration problems.

Peer-review under responsibility of the Scientific Committee of ATI 2015

Keywords:experimental tests, frequency analysis, noise, sound quality, vehicle refinement, vibration

1. Introduction

There are many sources of noise in a vehicle: in the past the engine was considered the most important, therefore the first NVH studies were applied to reduce noise and vibrations generated by the engine and powertrain. As over the years a strongly reduced level of noise has been reached for these systems, other sources of noise such as road noise have become very significant. Besides, the increase of the vehicle speed has strongly enhanced the importance of aerodynamic noise [1], as well. The engine provides a very important contribution to the annoying noise perceived inside a vehicle, representing a great source of internal vibration, too. The vibrations derive from the reciprocating and

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1876-6102
Peer-review under responsibility of the Scientific Committee of ATI 2015
doi:10.1016/j.egypro.2015.11.861

rotational masses such as pistons, connecting rods and shafts. Other sources of vibration come from the gearbox, the differential and the structural vibrating modes of the exhaust system .In addition, there are many acoustic sources in the powertrain system inducing airborne noise, and among them the most important are the intake and exhaust tailpipes. They act as very efficient acoustic sources and can be considered as monopole sources. The vehicle suspension system plays a key role in vibration transmission, being located in the structure-borne transmission path between the road–tyre interaction and the vehicle body. The tyres have a dual role in road-noise generation and transmission. On the other hand squeaks and rattles represent indirect noise sources, as they are generated by the dynamic displacement of the surfaces of the dashboard and internal trimmings, caused by the overall vibrations in a car. Besides the above main phenomena, there are other secondary noise sources, such as brakes, electrical and mechanical accessories, etc.

It is important to consider that internal vehicle noise does not depend only on the acoustic and vibration sources; key roles are also played by the different transmission paths between the sources and the receivers (i.e. the driver's and passengers' ears). In a vehicle there are two different categories of transmission paths, related to completely different mechanisms of energy transmission: structure-borne and air-borne paths. Commonly in a car, the structure-borne noise transmission path dominates at low frequency (<200 Hz) while the air-borne noise transmission path dominates above 500 Hz [2]. In the mid-frequency range, both transmission paths have usually the same level of importance.

In order to implement an improvement process of NVH performance of a vehicle, the knowledge of the main noise sources and the transmission paths represents a fundamental aspect.

This paper provides an overview of the main experimental techniques employed for the identification of noise sources in a vehicle. The description of the techniques will be supported by proper plots referred to experimentally analyzed case studies under actual urban driving conditions. The aim is to point out the role of experimental activity in identifying possible noise and vibration generation problems, which could affect vehicle sound quality and overall harmony [3].

Nomenclature

AI	Articulation Index
NVH	Noise Vibration Harshness
EFR	Engine Firing Rate
EMA	Experimental Modal Analysis
f_0	Engine firing frequency
k	Multiples of engine rotating frequency
N	Engine rotational speed
N_{cyl}	Number of engine cylinders
ODS	Operational Deflection Shapes
OMA	Operational Modal Analysis
PVL	Power Velocity Level
TPA	Transfer Path Analysis
u	Particle velocity magnitude
u_{ref}	Reference effective particle velocity
ε	Integer equal to 1 (for a two-stroke engine) or 2 (for a four-stroke engine)

2. Experimental techniques for NVH analysis in vehicles

Sound generation and transmission in a vehicle takes place in terms of small pressure waves that travel in air (air-borne noise), and vibrations that travel in vehicle structures (structure-borne noise). While air-borne noise involves a physical mechanism from which sound is generated and radiated (i.e. the hot displacement of fluid mass in the exhaust tailpipe), structure-borne noise is caused from a vibrating source that induces the acoustic energy to travel through solid structures and to be then released as air-borne noise (i.e. the engine structural vibrations). The main targets of NVH experimental techniques are to determine the characteristics of these two types of noise in a vehicle, as well as the transmission paths to driver and passengers. Only an accurate identification and characterization of noise and vibration sources could allow to realize new refinements in design and to validate the solutions, in order to improve vehicle interior sound comfort.

To date noise mapping techniques (sound intensity), acoustic holography and beam forming, Transfer Path Analysis, modal analysis, order tracking are considered the most relevant experimental techniques to analyze and identify NVH sources in a vehicle [4].Some of these techniques employ instrumentation which requires specifically constructed rooms such as anechoic or reverberant chambers. In fact, only in these particular controlled sound fields, the noisiness of a sound source can be easily related to the measured sound pressure ensuring sufficient accuracy. It is the case, for instance, of a typical condenser microphone, that if used in rooms that are neither anechoic nor reverberant could provide incorrect results, whether positioned too close to the sound source (at a distance less than the wavelength of the lowest frequency emitted from the source, that is the near field) or too far away from the source, where reflections from walls and other objects may considerably alter the measurement accuracy. Other measurement devices that need to be employed in free field conditions are the sound level meter and the traditional pressure-pressure sound intensity probe. However, thanks to the development of more innovative measurement techniques, sound intensity in-situ tests are now possible also where anechoic conditions are not applicable, like an engine bay or car interior. This technique relies on the use of the Microflown p-u intensity probe, the combination of a pressure microphone and a particle velocity transducer which directly measure close to the source surface the scalar value 'sound pressure' and the vector value 'acoustic particle velocity' in one spot, giving in output the sound intensity [5].Due to the near field benefits [6]using the direct measure of the directional particle velocity, p-u probes are not highly affected by background noise or reflections, and measurements can be undertaken in real operational situation. P-u probe represents an effective tool for vehicle noise sources identification issues. Typical measurements can be performed, for instance, on the engine compartment adopting the Scan & Paint method [7]. The acoustic signals of the sound field are acquired by manually scanning the emitting surface with the p-u probe while a camera is positioned toward the surface to film the scanning. The sensor position is extracted by applying automatic color tracking to each frame of the recorded video. It is then possible to directly visualize sound variations across the space in terms of sound pressure, particle velocity or acoustic intensity.

As an example, in the following figures results obtained scanning the engine bay of a four-cylinder four-stroke engine at a particular stationary operating condition (2000 rpm), are shown [8]. Fig. 1, in particular, reports acquired data processed in terms of Particle Velocity Level (PVL), which is by definition equal to:

$$\mathrm{PVL} = 20\log_{10}\frac{u}{u_{ref}}\left[\mathrm{dB}\right] \tag{1}$$

where u is the particle velocity magnitude and u_{ref} represents the reference effective particle velocity of 50 nano-meter per second. The engine radiated noise spectrum always contains strong excitations associated with the cylinder firings rate. The strongest tone in the spectrum is generally the Engine Firing Rate (EFR), defined as:

$$\mathrm{EFR} = \frac{N}{60\cdot\varepsilon}\cdot N_{cyl}\left[\mathrm{Hz}\right] \tag{2}$$

where N is the engine rotational speed expressed in revolutions per minute (rpm), ε is an integer equal to 1 or 2 for a two-stroke or a four-stroke engine respectively, and N_{cyl} represents the number of cylinders. The engine firing frequencies can be also expressed in terms of k-multiples of the rotating frequency, the so-called engine orders:

$$f_o = k\cdot\frac{N}{60}\left[\mathrm{Hz}\right] \tag{3}$$

According to formula (3) in a four-cylinder four-stroke engine the EFR is also called the 2^{nd}engine order, as the frequency is two times (k=2) the engine's rotation one.

As expected, in Fig. 1 the first PVL peak which is the dominant excitation in the spectrum represents the 2^{nd} engine order, whereas the subsequent three peaks correspond to multiples of the engine combustion frequency at 2000 rpm.

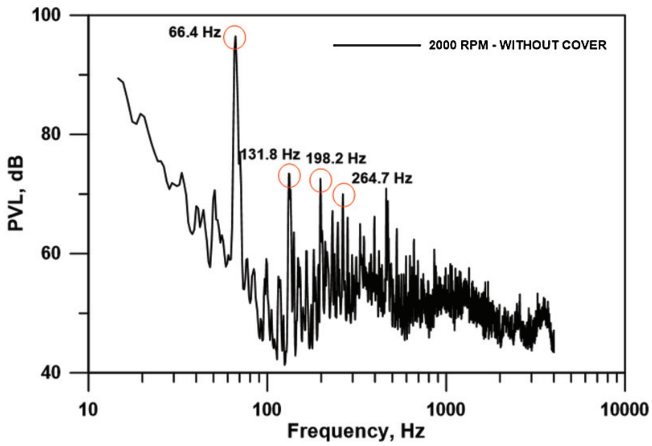

Fig. 1. Frequency spectrum of the particle velocity signal at 2000 rpm

This analysis can be also useful to identify occurrences not directly related to engine firings. For instance, in Fig. 1 the not negligible PVL peak around 500 Hzis likely due to a resonance effect of the system at this particular frequency.

As a final result, it is possible to visualize the sound field across the scanned space. In this regard, Fig. 2 shows the acoustic color map of particle velocity at the frequency of 66.4 Hz (the 2nd engine order). It is immediate to note that the main acoustic emissions come from the internal combustion engine, which radiates up to about 95 dB.

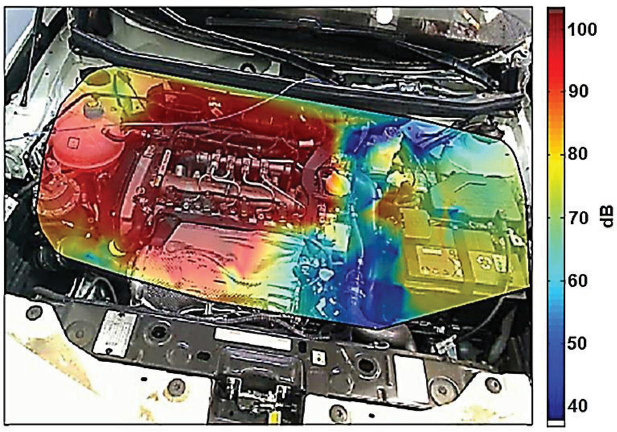

Fig. 2. Acoustic map of particle velocity at 66.4 Hz at 2000 rpm

This kind of sensor can be successfully used also for other applications in the field of mapping and analyzing automotive noise and vibration. Panel Noise Contribution Analysis, a well-known methodology for an air-borne Transfer Path Analysis (TPA) in car interior through which pressure contribution from the individual panels at a reference point can be very accurately calculated [9][10], or Near Field Acoustic Camera for sound source localization during transients even used in non-anechoic conditions [6], or In-Situ Absorption method for the measurement of the acoustic properties of materials [11][12], are typical tools employed for increasing the acoustic comfort quality in a car.

Order tracking analysis is another experimental technique which can provide useful information about vibrations and acoustic signals generated in vehicle drive train components, related to engine rotational speed and in particular to engine ignition frequency. In this respect, Fig. 3 shows an example of the spectrogram of exhaust noise signal acquired by a proper microphone located in the proximity of the tailpipe end, during engine run-up from approximately 1000 to 3500 rpm [13].

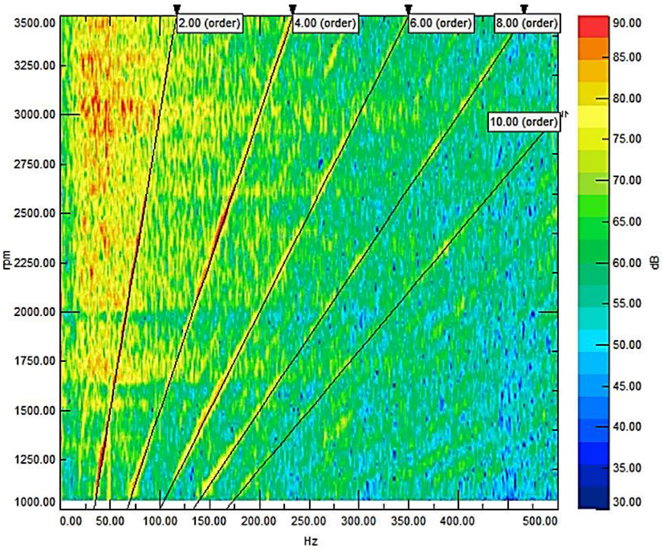

Fig. 3. 3D acoustic intensity map of exhaust noise signal in engine run-up condition from approximately 1000 to 3500 rpm

Such analysis allows to visualize the magnitude peaks of the spectrum lined up with the orders spectrum lines, and gives the possibility to identify the operating conditions and the frequency range of interest where noise emissions are predominant. By observing Fig. 3, it can be noted that most of the noise content is produced in a low frequency range up to approximately 350 Hz, with more pronounced peak values up to 100 Hz for engine rotational speeds above 2700 rpm. These latter could depend on a resonance effect related to exhaust natural frequencies to be better investigated.

Structural measurement techniques play a key role in the vehicle development process, as well. In particular, powertrain vibration isolation design, if carefully carried out, allows to minimize the structure-borne vibration transmitted from power plant to chassis and body structure. The most common acceleration transducer is the piezoelectric accelerometer which consists of a quartz crystal with a mass bolted on top. Accelerometers are able to detect very small vibrations and not be damaged by large vibrations in a wide frequency range from 0.2 Hz to 10 kHz. The main methods used for structural dynamics analyses are Experimental Modal Analysis (EMA), Operational Modal Analysis (OMA) and Operational Deflection Shapes (ODS).While the objective of traditional EMA is the construction of a mathematical model of the dynamic characteristics of the object under investigation by measuring the frequency response function between a force and a response transducers [14], OMA utilizes only response measurements of the structure in operational condition to identify modal characteristics. On the other hand, ODS allows to determine the real-world forced deflection during operation. With advances in performance of the test equipment and computer capabilities, modal analysis has become a standard tool in vehicle NVH development. The knowledge of the relevant dynamic characteristics helps engineers to avoid resonances at frequencies with high excitation, and therefore to reduce the risk of damage or strong structural vibration or sound pressure levels.

3. Vehicle sound quality

As explained, the knowledge and characterization of the different noise sources play a key role in the sound package design of a vehicle. However, although the level of interior noise reduction is very important for the acoustic comfort of the occupants, it is not sufficient by itself. Another important factor that has to be taken into account is the quality of the noise. In recent years there have been many sound quality studies and analyses in order to define the criteria for a noise that is not just quiet but also pleasant. Some of the most commonly used sound quality and psychoacoustic metrics for user's perception in a vehicle are Articulation Index (AI), Loudness and Sharpness [2].

The AI is a measure of the intelligibility of voice signals, expressed as a percentage of speech units that are understood by the listener when heard out of context. There are different algorithms for the calculation of the AI. The method used in the automotive field is based on the 1/3-octave band levels in dB(A) between 200 Hz and 6300 Hz, taking strongly into account the frequency bands where the typical speech frequencies are more important.

The Loudness level refers to the perceived intensity of the sound. It is based on the statistical response of the ear as a function of frequency for a statistically significant number of people. The unit of Loudness is “sone”, which allows to visualize the parameter on a linear scale. A sine tone of the frequency 1 kHz with a level of 40 dB has by definition a Loudness of 1 sone. The Loudness scale is distinguished by the fact that a tone which is perceived to have double the Loudness on the Loudness scale is designated by a doubled sone-value. For steady state sounds, standardized calculation procedures have been defined by Zwicker and Stevens and accepted as ISO standards [15][16][17]. For temporally varying sounds, Zwicker has also proposed an approach taking into account temporal effects [18]. The latter evolved until its acceptance as DIN 45631/A1 [19].

The Sharpness is another important measure that takes into account the frequency content of the noise. It is defined as the ratio between the high frequency noise level and the overall level; it is not related to sound intensity, but it is high for metallic noise components that are generally considered annoying. A high Sharpness is hence correlated with bad quality of the vehicle. The unit of Sharpness is “acum”. Sharpness delineates human sensation in a linear manner as well. The reference sound of 1 acum is a narrow-band noise, one critical band wide, and at a center frequency of 1 kHz and having a level of 60 dB. The Sharpness calculation is based upon the specific Loudness distribution of the sound. Therefore the calculation of the Loudness affects the results of the Sharpness analysis. The standard DIN 45692 standardizes the metric calculation.

An example of poor sound quality is represented by data reported in the following figures, [20]. In Fig. 4(a) the two lines on the graph represent the Time Varying Loudness measured in a four-cylinder engine vehicle by two conventional microphones located at the driver ears position, during engine run-up on a chassis dynamometer (red and green indicate left and right ear respectively).As highlighted in the circled region, the overall level, measured in this case in terms of Time Varying Loudness, exhibits strong deviations from the ideal trend (dashed blue line) at particular engine speed ranges, giving the impression of a vehicle not characterized by a smooth and refined ride. In effect, a vehicle signature that is loud but grows linearly with engine and vehicle speed will be more acceptable than a quieter signature that shows large deviations from its mean trend under the same test conditions.

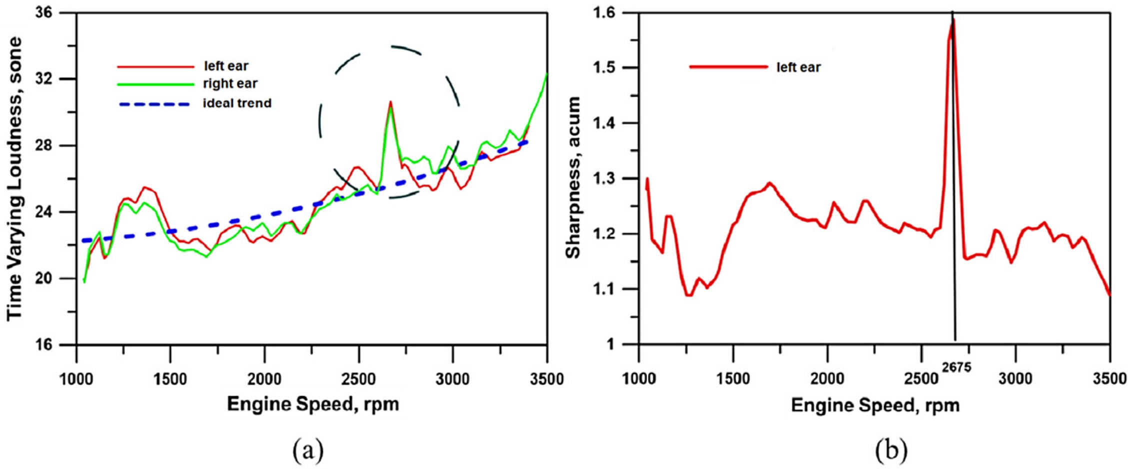

Fig. 4. Time Varying Loudness vs. RPM (a) and Sharpness vs. RPM (b) during vehicle acceleration

Also Sharpness plot in Fig. 4(b), which refers to the same test, indicates a low vehicle interior sound quality at a particular operating condition (around 2675 rpm), as it reaches a substantially high level.

The measure of the mentioned psychoacoustic parameters helps to identify the best solutions to improve NVH performance in terms of good interior sound quality rather than only reduced noisiness. Solutions can regard the use of appropriate materials which ensure adequate acoustic insulation and absorption of the vehicle cabin, as well as structural damping.

4. Conclusion

Several are the experimental techniques available nowadays for the characterization of vehicles noise and vibration. In this paper a review of the main relevant experimental methods has been provided together with experimental data representations of real analyzed case studies, with the aim to demonstrate how accurate measurements are very important starting points for identifying the causes of noise generation and for undertaking a successive improvement process of vehicles NVH performances.

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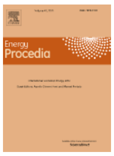

Biography

M. A. Panza was born in Cosenza in 23/06/1986 Italy, and graduated in Mechanical Engineering at the University of Calabria, Italy in 2012.She is currently a PhD Student in Industrial Engineering at University of Naples "Federico II", Italy, in collaboration with CNR - Istituto Motori, Italy. She is dealing with acoustic and vibration in automotive field.