Abouel-Seoud. 2015. *Int. J. Vehicle Structures & Systems*, 7(2), 71-76
ISSN: 0975-3060 (Print), 0975-3540 (Online)
doi: 10.4273/ijvss.7.2.05

International Journal of Vehicle Structures & Systems
Available online at www.maftree.org/eja

Influence of Road Roughness Parameters on Low Frequency Interior Noise in Off-road and Mid-size Passenger Vehicles

Shawki A. Abouel-Seoud
Automotive Engg. Dept., Faculty of Engg., Helwan University, Cairo, Egypt
Email: s_a_seoud@hotmail.com

ABSTRACT:
In this paper, assessment and evaluation of vehicle low frequency interior noise, infrasound closer to the threshold of hearing and their potential effects on human health are presented. The vehicle interior noise of off-road and mid-size vehicles was measured while driving on three different asphalt road surfaces. The results indicate that the vehicle acoustic comfort factor (VACF) should be at lower level for a relatively high acoustical comfort. Furthermore, at constant vehicle speed, the kurtosis parameter value is greater in high roughness road surface and is proportional to vehicle speed for every kind of road surface. Kurtosis has inverse effect on the VACF value. The VACF for road surface with higher roughness is lesser than the VACF for smoother road surface at same vehicle speeds.

KEYWORDS:
Low frequency sound; Vehicle acoustic comfort factor; Noise and vibration; Road index; Vehicle speed

CITATION:
S.A. Abouel-Seoud. 2015. Influence of Road Roughness Parameters on Low Frequency Interior Noise in Off-road and Mid-size Passenger Vehicles, *Int. J. Vehicle Structures & Systems*, 7(2), 71-76. doi:10.4273/ijvss.7.2.05

1. Introduction

Since last a few decades, a lot of studies have been carried out by automotive researchers to find the solution for passenger vehicle cabin interior noise. Reduction of the noise level improves the driving quality. Generally, noise generated by the vehicle system vibration in the vehicle interior affects driver's emotions and decreases the level of driving focus. This noise may also be described as a source of annoyance for human where unwanted noise may interfere with speech communication between passengers, and thus affecting driving concentration and sleep disturbance. Vehicle sound quality is one of the important factors used to evaluate vehicle performance. Previously most of the vehicle noise studies were dealt with quietness. Since last decade, it is also compulsory for industries to fulfil sound pleasantness requirements. The object of sound quality design is to achieve ideal vehicle acoustics in as many operating conditions as possible. A-weighted noise level and sound power are usually utilized to measure the noise but they are not adequate to characterize the impact of sound inside a vehicle. The most popular approach to determine the sound quality of a product is to define a specific index considering subjective and objective measurements simultaneously [1-4].

Assessment and evaluation of low frequency noise and infra sound close to the threshold of hearing and the potential effects on human health were presented. Low frequency noise generated by air flowing over a moving vehicle with the open window was chosen as a source of noise. The noise within the interior of the vehicle and its effects on driver's comfort at different speeds were analyzed. An open window at high speed behaves as a source of specifically strong tonal low frequency noise which was annoying. The interior noise of a passenger vehicle was measured while driving on normal highways and roadways. First, an octave-band analysis was used to assess the noise level and its impact on the driver's comfort. Second, a Fast Fourier Transform (FFT) analysis was used for the detection of tonal low frequency noise. Finally, it was suggested that the possibilities for scientifically assessing and evaluating the low frequency noise but not only for the presented source of the sound [5].

Low frequency noise can be more noticeable in-doors. Hence, it is often associated with attention reduction, sleep disturbance and adverse effects on health. Another problem is that low frequency noise travels farther than noise at higher frequencies. Hence, the source of low frequency noise is often difficult to trace. A large proportion of sound is generated by the mechanical vibration of a solid component of the buildings structure and/or by the equipment in the buildings as was experimentally proved in [6]. The mechanical energy involved has often been transmitted from remote mechanical or acoustical sources by means of audio-frequency vibration waves propagating in connected structures, which is typical for structure-borne sound. The subject of structure-borne sound is far more complex than that of air-borne sound. Air can support longitudinal acoustic waves only. Two fundamental forms of vibration waves can exist in un-bounded elastic solids because they can support shear stress. This paper focuses on low frequency noise generated by open windows of a moving car. This type of noise is very strong and is a good example of why it is necessary to assess and evaluate by different methods as of today [7].

Nowadays people spend a considerable amount of day-time (10-20%) for travelling in and out of urban environment using different transportation systems such as bus, metro, tram, ferryboat, car and train. This phenomenon is increased due to expansion of cities and mobility demand due to globalization factors. Exposure to noise and vibration levels associated to these routine activities cannot be negligible. Often even comfort conditions were poor and did not permit to use the long travel time for other activities such as reading and talking. An overview of investigation studies to assess the problem and recent research projects in this field were presented and discussed [8]. Vehicle passengers are exposed to complex stimuli, and their evaluation of the product is strongly dependent on all of the encountered stimuli. Some interactions between sensorial modalities may exist. With regards to sound and vibration, which are often due to the same sources in vehicles, many studies have been conducted. From the great variety of stimuli used in the literature, it seems that sound can have an effect on vibration perception. An important aspect is related to the contribution of sound and vibration to the overall evaluation of the multi-sensorial situation. Both sound and vibration significantly contribute to the evaluation, unless one stimulus is strongly dominant. It was shown that such multi-sensorial models could be dependent on test subjects. Steering wheel vibrations had to be taken into account by only half of the jury, while seat vibrations and noise were important for all subjects [9-10].

Noise, Vibration and Harshness (NVH) is an essential factor for vehicle industries to improve the quality of the products and to reduce the interior noise in passenger vehicle cabin. To reduce cost of designing and cost of manufacturing in automotive industries and to manage the time of conceptual design process, machine element designing and interior noise modeling had been carried out at the first step of conceptual and elements design. Reduction of booming noise is very important in the design process. To reduce the time of engineering analysis, it is essential to investigate the booming noise before manufacturing of primary prototype of a passenger vehicle [11]. In a dynamic system, transmission of sound depends on frequency, direction of the input motion and characteristics of the output. On the other hand, the surface characteristics of road pavements have a significant impact on the generation of vehicle noise. Road surface texture as well as sound absorption and elasticity are crucial factors for mechanical interaction and aerodynamic processes within the tire/road contact. These road surface characteristics are relevant for the generation of rolling noise.

For a quantitative ranking of contributions from several sources to a response, Operational Transfer Path Analysis is used to calculate the transfer functions between selected source and response channels through singular value decomposition. For the analysis, several multi-channel measurements, containing synchronous data for structure and air-borne sound in different operating conditions were performed. The transfer functions calculated from an engine run-up measurement are used to analyze the contributions of the main sound sources over the dominant transfer paths to the vehicle interior noise. In addition, the excitation from the main source was altered while all other aspects of the source and structure were kept the same. In this experiment the engine excitation was altered by changing parameters of the engine control unit. Using the calculated transfer functions, predictions of the vehicle interior noise for the altered excitations were evaluated. The resulting sound pressure level of the calculated vehicle interior sound was in accordance with the values from the original measurements [12].

The above review has shown that most of the efforts which had been done in this subject were directed towards studying the vehicle low frequency interior noise characteristics with respect to road surfaces. Their contributions were limited due to ignoring the consideration of road roughness parameters. In some cases the experimental simulation has carried out within the laboratories using chassis dynamometer. The review has established that, there is a need for more investigation on the vehicle noise characteristics with respect to road surfaces out-door. Consequently, there is a general attention to establish more parameters by which the vehicle low frequency interior noise can be characterized. To achieve this objective, this study was carried out as a contribution to the international harmonization of methods, measurement, assessment and evaluation of vehicle low frequency noise from all external and internal sources in enclosed spaces. Mid-size Saloon vehicle (MSV) and Off-road vehicle (ORV)) were used and measurements were carried out on smooth, spalled and coarse asphalt road surfaces at various vehicle speeds. Based on the principles described in this paper, the background can be set for further research in this area.

2. Road roughness parameters

Road roughness, vehicle suspension and driver's behaviour (including choice of speed) are the main sources of vibration transmitted to the vehicle passengers. Within reasonable variations in these factors, road roughness plays a considerably greater part than the other two [13]. All of these three sources are playing important role in vehicle acoustic quality. In order to assess the road roughness on vehicle interior noise, International Roughness Index (IRI) and Kurtosis are used. IRI is a general pavement condition indicator that summarizes the roughness qualities which affect the vehicle response. IRI is the most appropriate when a roughness measure is related to overall ride quality and overall surface condition [10]. Many attempts have been made to find out the IRI which can be defined [13] as,

$$\frac{(a)_{rms}}{IRI} = 0.16\left(\frac{v}{80}\right)^{1/2} \tag{1}$$

Where v (km/h) is the vehicle speed and $(a)_{rms}$ is the vehicle floor RMS acceleration vibration (m/s^2). For this purpose, Bruel & Kjaer accelerometer is installed on the floor of the vehicle compartment to measure the vertical vibration at specific speed. By using Eqn. (1), the IRI value of the road can be found at constant vehicle speed read from the speed panel.

Kurtosis is a measure of the impulsiveness of the time domain signal distribution detected by the accelerometer and relates to the characteristics of the road. The method exaggerates the impulses in the sound and a high Kurtosis value normally reflects poor sound quality [14]. Kurtosis can be defined as,

$$Kurtosis = \frac{1}{N}\sum_{n=1}^{N}\left(x(n)-\bar{x}\right)^4 \bigg/ \left[\frac{1}{N}\sum_{n=1}^{N}\left(x(n)-\bar{x}\right)^2\right]^2 \quad (2)$$

Where N is the number of data points taken in the signal, x (n) is the amplitude of the signal at the n[th] point, and $\bar{x}$ is the mean value of all amplitudes.

3. Vehicle interior noise parameters

The sound heard by human ears would be analyzed by the brain through the auditory system based on its frequencies and amplitudes. The selected objective metrics are measurements of frequency and amplitude modulations throughout the spectrum. So an attempt to find the quality of sound based on these metrics has good correlation to subjective evaluations. The basic choice to be made is between constant absolute bandwidth and constant proportional bandwidth where the absolute bandwidth is a fixed percentage of the tuned centre frequency. Constant percentage bandwidth (CPB) gives uniform resolution on a linear frequency scale. However, the linear frequency scale automatically gives a restriction of the useful frequency range to (at the most) two decades. It is worth paying attention to the first and third octave CPB filters since these are widely used in acoustic measurements. The former have a bandwidth such that the upper limiting frequency of the pass band is always twice the lower limited frequency, resulting in the band width of 70%.

Vehicle acoustic comfort factor (VACF), as defined below, is used for the assessment and evaluation the vehicle interior noise:

$$VACF = \sqrt{\frac{1}{N}\sum_{n=1}^{N}\left(x(n)-\bar{x}\right)^2}, \ \bar{x} = \frac{1}{N}\sum_{n=1}^{N}x(n) \quad (3)$$

Where N is the number of data points taken in the signal, x (n) is the amplitude of the signal at the n[th] point, and $\bar{x}$ is the mean value of all amplitudes. Measurement and analysis of the road conditions contributed parameters and correlation with VACF can give useful information about the effect of road roughness on the passenger auditory perception.

4. Measurement methodology

Road noise generally starts to be noticeable at vehicle speeds above 50 km/h, but its maximum contribution to the overall interior noise is between 60 and 100 km/h and then decreases at higher speeds, where aerodynamic noise becomes predominant. For this reason, tests for road noise are generally conducted at constant conditions, typically 80 km/h and in coast down on different road surfaces. Road noise is generated by the interaction between the tire and the road surface and excites the vehicle through structural and airborne paths [15]. To measure vehicle interior noise characteristics up to 400 Hz, the relevant physical effects have to be considered. Three main groups of vehicle areas interacting with one another and influencing the interior noise can be selected. These are vehicle body structure, the fluid enclosed in the passenger room, cavities behind covers and the trim parts connected to the car body [16].

In present work, two vehicle interior noises were prepared using the binaural recording technique with a signal length of 1 second and a sampling rate of 2048 Hz. Three road surfaces were selected as the test roads. Around the test site, there were no sound reflecting buildings and other objects within 50 meters. Under each working conditions, the noise signals at the driver's head position were measured by using a Bruel & Kjaer portable multi-channel PULSE Type 3560-B-X05 analyzer with labshop software type 7700 and then saved in the computer. During measurement, the microphones were arranged at 0 or 0.2 meters from the centreline of the seats with a height of 0.7 meters, depending on the seated conditions, as shown in Fig. 1. The specifications of ORV & MSV used in the measurements are given in Table 1. The characteristics of the selected road surfaces for this study are described in Table 2 and their photographs are shown in Fig. 2.

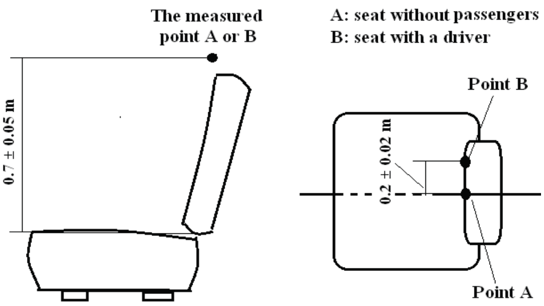

Fig. 1: Microphone arrangement for noise measurements

Table 1: Test vehicles description

Vehicle	Front suspension system	Rear suspension system	Tyre size
ORV	Coil springs over shocks, upper and lower A-arms.	Multi leaf springs and shocks.	175\70 R16
MSV	Macpherson strut with shocks and coil spring, 1 piece lower control arm.	Coil springs over shocks, trailing arms, 3 lateral links.	175\70 R13

Table 2: Description of road surfaces used in the test

Type of road	Road surface appearance	Road surface characteristics
Smooth Asphalt	Smooth asphalt, no wear or weathering, small stones, smooth surface.	Low overall level, higher frequency greater proportion of noise, no "roar"
Spalled Asphalt	Asphalt mechanically roughened to resurfacing, pattern not complete random, large polished stones, moderately dense aggregate	Pure tone, moderate "roar," high overall level
Coarse Asphalt	Asphalt, small medium rough stones, very dense aggregate	Broadband "roar" medium overall level.

(a): Smooth **(b): Spalled** **(c): Coarse**

Fig. 2: Asphalt road surface roughness asphalt road surface

The vibration measurements were made in smooth, spalled and coarse asphalt road surfaces and the vibration samples were acquired with integration period of 1 second. Un-weighted accelerations on the floor were measured. One Bruel & Kjaer accelerometer Type 4514B-001 mounted upon the vehicle floor was used to measure the vibration acceleration signals. The vibration amplitudes recorded from the floor during travel are investigated for possible artefacts and any unclear signals detected are removed. The vibration measurements in terms of RMS accelerations in vertical direction were truncated to show the frequency range of interest which is up to 400 Hz. Noise generated in a moving vehicle was investigated as a good representative source of strong low frequency noise. The noise level was measured in terms of Sound Pressure Level (SPL) by 1/2-microphone Bruel & Kjaer Type 4189-A-021 inside the test vehicles with all vehicle windows closed. During the measurements the vehicle was driven on the road surfaces with minimal traffic. The measurements were taken at various vehicle speeds ranging from 20 km/h to 100 km/h. A schematic of experimental setup is shown in Fig. 3.

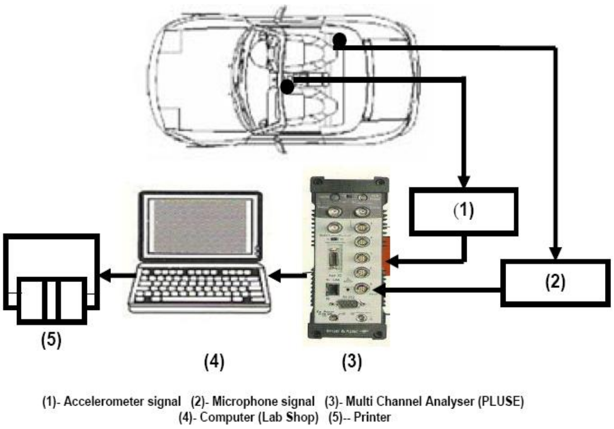

Fig. 3: Schematic of experimental setup

5. Results and discussion

The FFT vibration acceleration and SPL measurements are shown in Figs. 4 and 5 respectively. The dispersion of peak values is 0.185 m/s^2 and 3 dB. This difference can be caused by the variation of vehicle speed or air flow velocity around the vehicle. The frequency variation ranges from to 1 Hz to 2.5 Hz. The response values exceeded 0.877 m/s^2 and 95 dB. The SPL and vibration acceleration response are close to the threshold of pain. Figs. 6 and 7 show the vibration acceleration on the floor of MSV and SPL at driver's head position respectively. The road surface is coarse asphalt and the vehicle speed is 100 km/h. Figs. 8 and 9 show the influence of vehicle speed and road surface on the 1/3-octave band frequency of weighted SPL in terms of dB (A) for ORV and MSV respectively. The SPL is considerably changed for both vehicle speed and type of road surface. Some discrepancies existed in low 1/3-octave band up to 63 Hz for ORV speed of 100 km/h at smooth asphalt road surface with off-road vehicle (Fig. 8) and 1/3-octave band up to 25 Hz for MSV speed of 100 km/h for all types of road surface. The 1/3-octave band frequencies SPL for MSV and ORV at vehicle speed of 80 km/h on spalled and coarse asphalt road surface are presented in Figs. 10 and 11 respectively. The behaviour of MSV on spalled asphalt road surface is lower than ORV. This is due to the design of MSV's front and rear suspension systems which absorb more vibration than that for ORV. Figs. 12 and 13 show examples of the floor vibration acceleration in terms of Kurtosis and the RMS generated interior noise in terms of SPL for MSV interior at 100 km/h on coarse asphalt road respectively.

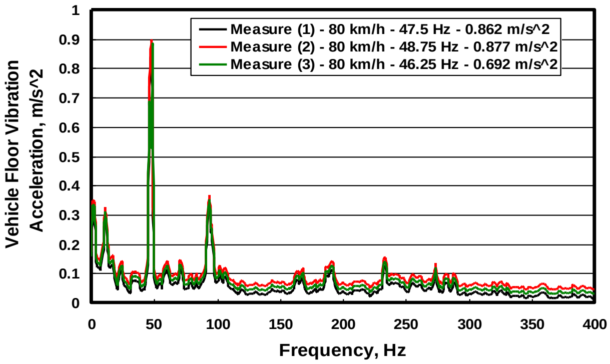

Fig. 4: FFT analysis of floor vibration acceleration in ORV interior at 80 km/h on coarse asphalt road

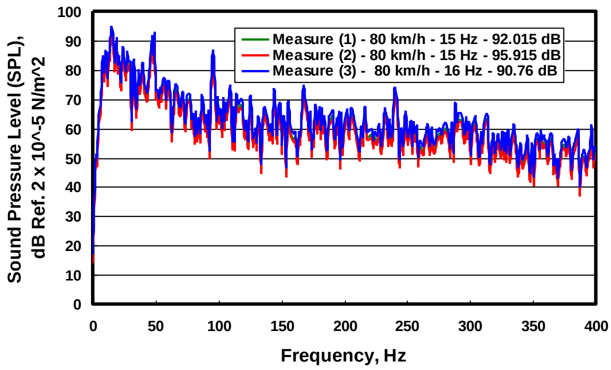

Fig. 5: FFT analysis of generated noise in ORV interior at 80 km/h on coarse asphalt road

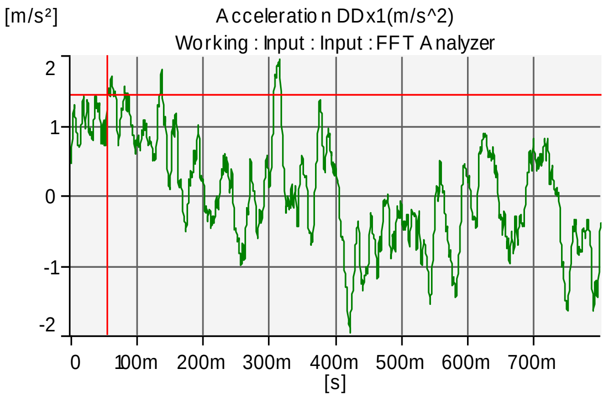

Fig. 6: Time history of MSV floor vibration at 100 km/h on coarse asphalt road surface

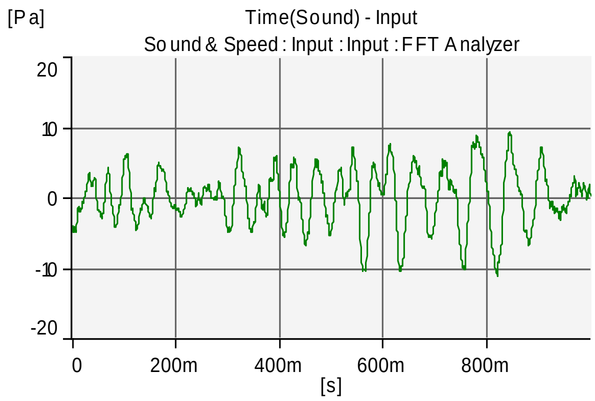

Fig. 7: Time history of MSV interior nose at 100 km/h on coarse asphalt road surface

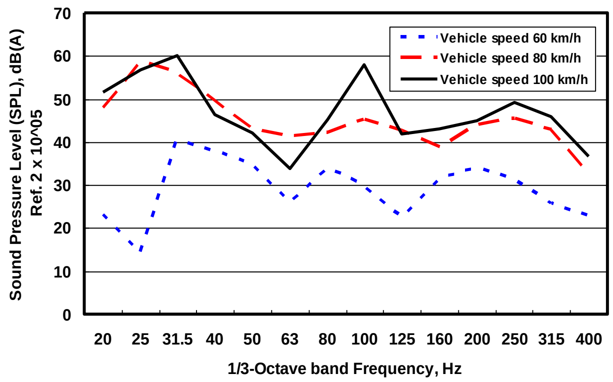

Fig. 8: 1/3-Octave band frequency SPL for ORV at different vehicle speeds on smooth asphalt road surface

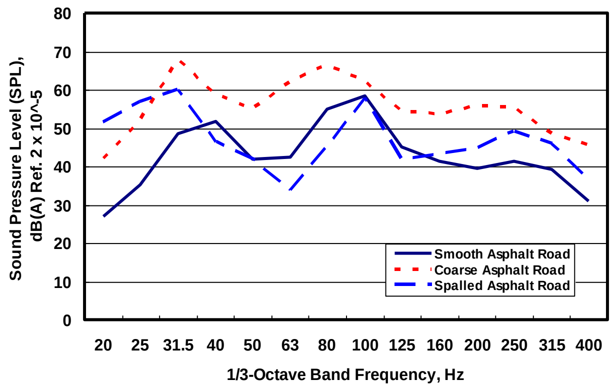

Fig. 9: 1/3-Octave band frequency SPL for MSV at vehicle speed 100 km/h on different road surfaces

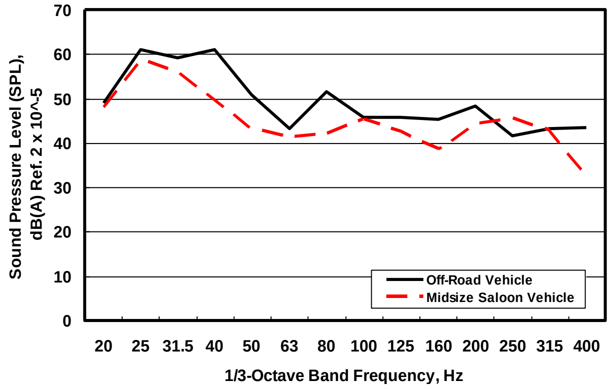

Fig. 10: 1/3-Octave band frequency SPL in ORV & MSV for vehicle speed 80 km/h on spalled asphalt road surface

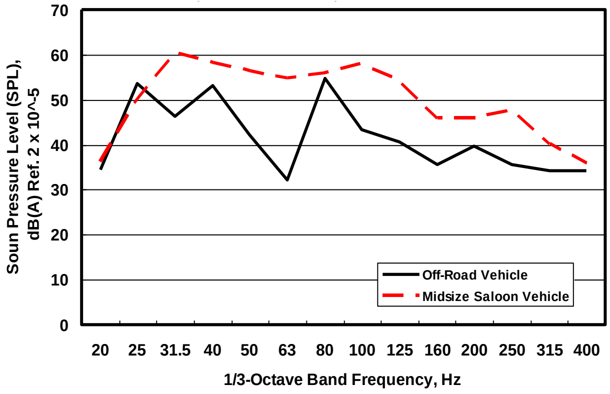

Fig. 11: 1/3-Octave band frequency SPL in ORV & MSV for vehicle speed 80 km/h on coarse asphalt road surface

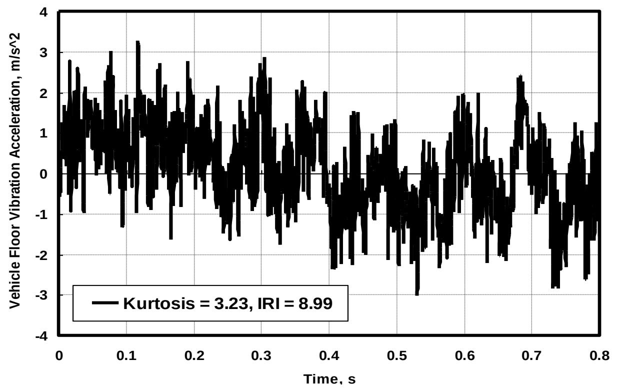

Fig. 12: Time history of the floor vibration acceleration in the MSV interior at 100 km/h on coarse asphalt road

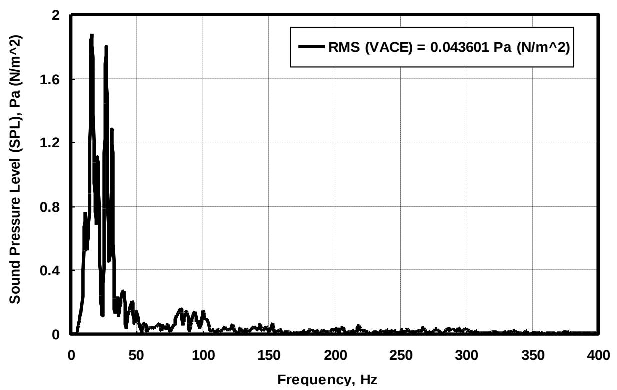

Fig. 13: FFT analysis of generated noise in MSV interior at 100 km/h on coarse asphalt road

The influence of road roughness parameters of Kurtosis and IRI on VACF are presented in Table 3. The value of Kurtosis should be approximately 3 for a Gaussian distribution. Higher Kurtosis indicates the existence of numerous extreme data values and inconsistent with a Gaussian distribution. Whilst Kurtosis lesser than 3 designates a relatively flat distribution. Nearly all the Kurtosis values are lower than 3, therefore, they are in flat distribution. Generally, it can be stated that the distribution of Kurtosis against vehicle speed variation can be noticed. At constant vehicle speed, Kurtosis is greater in road surfaces with high roughness. Kurtosis is proportional to the vehicle speed for each kind of road surface. Kurtosis has an inverse effect on the VACF. However, an increase in the value of kurtosis results in reduction of the VACF. Furthermore, in road surfaces with greater roughness, the values of VACF are less than those of the road surfaces with smoother surfaces for the same vehicle speed. IRI values are proportional to Kurtosis which indicates that human audition perceives more peaks and impulses when driving on road surfaces with greater roughness. IRI has inverse effect on human comfort, which shows reduction of the VACF values.

Table 3: Results summary for ORV and MSV interior noise

Asphalt road type	Vehicle speed, km/h	ORV			MSV		
		60	80	100	60	80	100
Smooth	Kurtosis	2.06	2.04	2	2.24	2.68	2.87
	IRI	8.19	9.1	9.32	4.87	4.56	4.39
	VACF	44.72	49.85	51.33	36.92	43.75	49.87
Spalled	Kurtosis	3.39	3.37	3.21	2.66	2.47	2.23
	IRI	6.92	7.06	8.11	9.74	11.6	11.9
	VACF	54.97	55.44	59.38	55.17	56.7	60.8
Coarse	Kurtosis	3.07	3.18	3.23	2.83	2.91	3.08
	IRI	8.8	8.93	8.99	8.23	7.44	8.09
	VACF	57.45	59.01	64.78	48.46	50.09	52.34

6. Conclusions

The influence of road surface roughness on the vehicle interior noise up to 400 Hz has been described in this paper. It is found that the spalled asphalt road surface is the quietest compared with smooth and coarse asphalt road surfaces. The spalled road surface provided relatively higher estimation on basis of SPL in terms of dB (A). To have a relatively high acoustical comfort, VACF should be at a lower level. At constant vehicle speed, Kurtosis is greater in road surface with high roughness values. Kurtosis is proportional to the vehicle speed for every kind of road surface. Kurtosis has an inverse effect on the VACF value. Road surface with higher roughness has an amount of VACF less than the road with smoother surface for the same vehicle speed.

REFERENCES:

[1] H.H. Priebsch, I. Hauer, H. Fellner and G. Polt. 2001. Numerical Simulation of vehicle interior noise up to 250 Hz, *Proc. Styrian Noise, Vibration & Harshness Congress*, Graz, Austria.

[2] M. Schneider, M. Wilhelm and N. Alt. 1995. Development of vehicle sound quality-targets and methods, *SAE Paper 951283*.

[3] F. Rossi, A. Nicolini and M. Filipponi. 2003. An index for motor vehicle passengers acoustical comfort, *Proc. 32nd Int. Congress and Exposition on Noise Control Engg.*, Seogwipo, Korea.

[4] M.J. Mohd Nor, M.H. Fouladi, H. Nahvi and A.K. Ariffin. 2008. Index for vehicle acoustical comfort inside a passenger car, *Applied Acoustics*, 69, 343-353. http://dx.doi.org/10.1016/j.apacoust.2006.11.001.

[5] S. Ziaran. 2013. Low frequency noise and its assessment and evaluation, *Archives of Acoustics*, 38(2), 265-270. http://dx.doi.org/10.2478/aoa-2013-0032.

[6] S. Ziaran. 2011. Effects of low-frequency noise in closed space on the human, *Proc. 40th Int. Congress and Exposition on Noise Control Engg.*, Osaka, Japan.

[7] S. Ziaran. 2012. Low frequency noise from the open window in a moving car and its effect on human being, *Proc. 41st Int. Congress and Exposition on Noise Control Engg.*, New York, USA.

[8] L. Maffei. 2009. Acoustic and vibration and vibration and comfort inside urban and extra-urban transportation systems, *Proc. 16th Int. Congress Sound and Vibration*, Krakow, Poland.

[9] S. Viollon, C. Lavandier and C. Drake. 2002. Influence of visual setting on sound ratings in an urban. environment, *Applied Acoustics*, 63(5), 493-511. http://dx.doi.org/10.1016/S0003-682X(01)00053-6.

[10] S. Amman, R. Meier, T. Mouch and P. Gu. 2005. A survey of sound and vibration interaction, *SAE Paper 2005-01-2472*.

[11] H.D. Lee, W.S. Hwang and M.E. Kim. 2000. Booming noise analysis in passenger car using a hybrid-integrated approach, *SAE Paper 2000-01-0723*.

[12] J. Putner, H. Fastl, M. Lohrmann, A. Kaltenhauser and F. Ullrich. 2012. Operational transfer path analysis predicting contributions to the vehicle interior noise for different excitations from the same sound source, *Proc. 41st Int. Congress and Exposition on Noise Control Engg.*, New York, USA.

[13] K. Ahlin, S.E. Tech and J. Granlund. 2001. *Int. Roughness Index, IRI, and ISO 2631 Vibration Evaluation*, Transportation Research Board, Washington DC, USA.

[14] Bruel & Kjaer. 2004. *Introduction to Sound Quality - Lecture Notes*.

[15] S.W. Kang, J.M. Lee and S.H. Kim. 2000. Structural-acoustic coupling analysis of the vehicle passenger compartment with the roof air-gap and trim boundary, *J. Vib. Acoust.*, 122(3), 196-202. http://dx.doi.org/10.1115/1.1302984.

[16] S.D. Lee. 2006. Characterization of multiple interior noise metrics and translation of the voice of the customer, *Int. J. Vehicle Noise & Vibration*, 2(4), 337-351. http://dx.doi.org/10.1504/IJVNV.2006.012784.