Response Surface Methodology for Objective Evaluation of Vehicle Interior Noise

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Abstract: - The importance of acoustic comfort has grown in the past few years in case of passenger cars, since regarding consumer side, the quality of the vehicle is strongly influenced by that criterion. In this paper the sound pressure level of passenger vehicle was investigated. A B-segment estate car was chosen for the acoustic experiments as sample vehicle. Input data were varied in three levels containing qualitative (working condition of the vehicle) and quantitative (excitation from the outer environment) ones as well. Pink noise was chosen as measurement signal and the values of the generated equivalent continuous sound pressure level were registered in the cabin in case of each possible combination of the levels of the input variables. Based on the measured data, a second order empirical model was constructed by help of response surface methodology (RSM). The accuracy and the conformity of the equation were investigated by help of the residuals. The applicability of the formula was verified by further confirming measurements. Investigations revealed that the residuals follow Gaussian distribution in both cases, what is more, have small-scaled standard deviation. As a consequence, the presented formula is proper for calculating the sound pressure level of the vehicle interior with an adequate accuracy within the range of the parameters examined.

Keywords: - vehicle interior noise, sound quality, equivalent continuous sound pressure level, response surface methodology, RSM

1. INTRODUCTION

Nowadays, passenger cars have to meet complex requirements. Travel comfort is one of the most important criteria from consumer side that means even the ergonomic design of the interior and the acoustical well-being as well. Since reducing the audibility of sound effects from the environment (road-, traffic- and other unwanted noises), the so-called noise insulation of the cabin is gaining importance. Nevertheless, the complete exclusion of the sound effect coming from outer sources conflicts road safety issues.

Regarding minor vehicle collisions in which cases the impact speed is v_i = 1 … 5 km/h [1], the perceptibility of the incident is the key question. However, the method of the investigation is not entirely clear.

According to Schneider [2], the appreciability is based on three fields. Visual perception is characterized by the direction of the driver's view. In many cases of low speed collisions poor visibility is provided that makes the decision more difficult. Furthermore, acoustic detectibility is to study as well. That means the audibility of the sound effect caused by the impact. This issue is influenced by numerous parameters. First of all, the acoustic insulation of the cabin and the background noises from inner (comfort electronic systems, speech of passengers, etc.) and outer sources (road, traffic, engine noises and environment) deteriorate the perception via hearing. The third way is the tactile and kinesthetic appreciability that is in connection with the sense of balance. In this case, the location of the contact is to examine since as a result of the complex requirements the parts of the vehicle body do not have the same stiffness.

On the one hand, the outer environment significantly impacts the sound quality of the vehicle interior. In addition, the disturbances derived from the inside influences the acoustic appreciability in a great extent. Several studies verified the connection between the company travelling in the vehicle and the likelihood as well as the severity of the collision, since peer pressure in terms of driving is an extremely central issue.

Orsi et al. [3] examined the effect of the presence or absence of passengers on the outcome of the accident in aspect of the driver's injury, based on police reported incidents in Pavia, Italy, in 2004-

2005. It was stated that the presence of passengers is a controversial issue. In case of young drivers (aged under 25 years) the risk of injury was higher when company was present. On the other hand, adult drivers were inclined to take part in single-vehicle crashes when driving alone.

Chan et al. [4] investigated the impacts of a passenger driver attention and performance. Two levels of driving tasks were performed in driving simulator in a sound-attenuated, electrically shielded room. It was revealed that the more difficult scenario resulted poorer driving performance. Furthermore, more attentional focus is required when having in-car passengers.Bose et al. [5] investigated the risk of driver fatality on fatal frontal crashes occurred in the USA (2001-2009). Models newer than 1998 with steering wheel mounted airbag and only belted drivers were involved in the analysis. By help of multivariate logistic regression, the hypothesis was evaluated whether the presence of unrestrained rear seat passengers (sitting in the second row) increases the likelihood of driver injury severity using multivariate logistic regression analysis.

Chung et al. [6] aimed to study the influence of the presence of a defined type of passenger on the driving habits of young Korean drivers in a driving simulator. Three groups of automobilists were set: the first drove alone, the second with a silent passenger and the third with an active one who provided tips on driving safety. It was stated that the advisor passenger made the drivers slow down, however, the other groups did not show a significant difference regarding driving speed.

Rosenbloom et al. [7] carried out traffic observations in order to reveal connections between the presence of passengers and the likelihood to commit violations. Their results indicated that drivers performed safer driving behavior when passengers were travelling in the vehicle, namely, higher likelihood of seatbelt use and lower one of violating. In addition, it was demonstrated that having a child among the passengers, the driver undoubtedly commits less violation that driving solo.

The appreciability of pure sine tones in the vehicle interior had already been studied [8]. It was revealed that the acoustic perceptibility inside the vehicle is influenced by several parameters. The aim was to sort out the factors having a significant effect on the detectability of pure sine tones by help of significance test. Based on the Pareto Charts, it was stated, that operating the internal combustion engine and the fresh air fan, as well as the position of the front left window were the most influential parameters.

Angelescu et al. [9] examined the effect of the heating, ventilation and air-conditioning (HVAC) system on the cabin noise based on the input mode of the airflow introduced into the vehicle interior. Four types of ventilation grids (an initial, and three prototype ones) were analyzed. The experiments revealed that the sound produced by the fresh air fan is the most important component of the interior noise. In addition, the initial grid was found to be the most comfortable in acoustical sense.

In this paper, the resulting noise was investigated in the vehicle interior. During airborne sound measurements the equivalent continuous sound pressure level was registered and empirically modelled by help of response surface methodology.

2. MATERIALS AND METHODS

2.1. Sample vehicle

The acoustic experiments were carried out on a SKODA FABIA COMBI sample vehicle. The chosen B-segment estate car was equipped with a 3-cylinder gasoline engine. Further technical parameters are shown in Table 1.

Table 1. Technical data of the sample vehicle

Manufacturing. year	2004
No. of valves	12
Displacement	1198 ccm
P_{max}	47 kW

2.2. Devices used

During the investigation a Hohner Stereo 50 portable sound system with double speakers was used as noise generator. In addition, a Svantek 959 Sound& Vibration Analyzer was equipped with the possibility of observing the sound pressure levels in 1/3 octave.

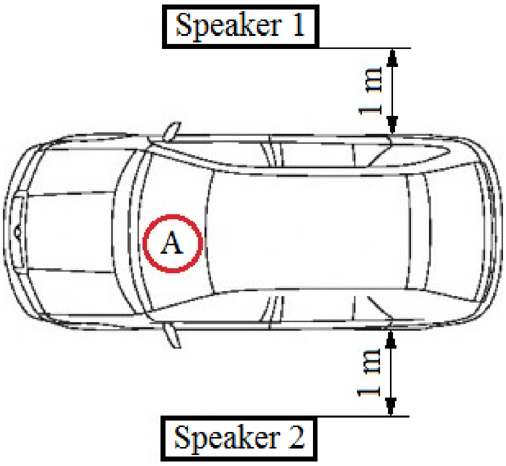

Figure 1. Experimental setup

2.3. Experimental setup

The experimental setup is shown on Figure 1.

During the experiments, the speakers were placed at a distance of 1 m of the sample vehicle. The recommendations of ISO 5128-1980 [10] and Putra et al. [11] were taken into account during the experiments: all the doors and windows were closed, furthermore, the sound analyzer was put in the driver's right ear position (see on Figure 1. marked with an "A").

2.4. Methods used

Response surface methodology (RSM) was used to evaluate the measurement which contains mathematical and statistical techniques in order to effectively model and analyze problems influenced by more variables. The name comes from the graphical representation, since having two input parameters and illustrating the output plotted against the independent variables, a surface can be seen on a 3-dimensional coordinate system. The method can be used in case of more independent variables as well, however, the depiction is more difficult.

To find the relationship between the input and output parameters, approximating function can be defined. A second order one with two independent variables is shown in Eq. (1)

$$y = \beta_0 + \beta_1 \cdot x_1 + \beta_2 \cdot x_2 + \\ + \beta_{11} \cdot x_1^2 + \beta_{22} \cdot x_2^2 + \beta_{12} \cdot x_1 \cdot x_2 + \varepsilon \qquad (1)$$

where y is the output; β_0, β_1, β_2, β_{11}, β_{22} and β_{12} are empirically determined constants; x_1 and x_2 are independent input variables and ε represents the error of the examined function [12][13].

2.5. Adaptation

Since it can be stated that the internal noise level significantly depends on the sound pressure level of the external environment. Thus, the exterior excitation was chosen as the first independent quantitative variable. In the investigations pink noise was used as outer excitation, in which each octave carries the same amount of noise energy [14].

In addition, based on previous studies [8] [9] multiple working conditions were investigated which was the second, but qualitative input parameter. Both independent variables were set in three level (see Table 2).

Table 2. Levels of the input variables

Level	Working condition	Excitation
	x_1, -	x_2, dB
0	without operating the engine	71.2
1	engine at idle	80.5
2	engine at idle + FAF at level II	95.6

In order to objectively quantify the sound quality of the car interior, the equivalent continuous sound pressure level (L_{Aeq}, dB) was registered, that means a constant noise level providing the same noise energy as the measured varying sound in a given period of time [15].

A second-order approximating function was generated in the form of Eq. (1), where the output parameter was the recorded equivalent continuous sound pressure level.

3. INVESTIGATIONS

3.1. Measurements

Airborne sound measurements were carried out in quiet enclosed space.

Since both independent input variables were varied at three levels, the experimental design contained nine measurement points these were all possible combinations of the levels.

During the investigations each setting was measured twice and the equivalent continuous sound pressure level was registered.

3.2. Results

The results of the airborne sound measurements can be seen in Table 3.

Table 3. Experimental results

Exp. runs	x_1, -	x_2, dB	$L_{Aeq\ int1}$ dB	$L_{Aeq\ int2}$, dB	L_{Aeqm}, dB
1	0	71.2	47.1	47.3	47.20
2	0	80.5	57.5	57.4	57.45
3	0	95.6	72.7	72.8	72.75
4	1	71.2	49.2	49.5	49.35
5	1	80.5	60.1	60.3	60.20
6	1	95.6	72.6	72.7	72.65
7	2	71.2	55.3	55.4	55.35
8	2	80.5	60.5	60.3	60.40
9	2	95.6	72.3	72.0	72.15

In addition, the mean value of the measured ones were calculated (L_{Aeqm}, dB) for each measurement point.

3.3. Evaluation

In the evaluation Minitab 17 was used.

Firstly, the influence of the input parameters on the equivalent continuous sound pressure level of the car interior was studied. Its graphical representation is shown on the main effects plot (see Figure 2.).

Regarding Figure 2, it can be stated that inhancing the level of both independent variables have a nearly linearly increasing effect on the output parameter. However, the influence of working condition is less remarkable as the line has a lower slope. Since the graphical representation of the main effects plot is nearly linear and is not horizontal, both input variables have a noticeable influence on the equivalent sound pressure level of the vehicle interior.

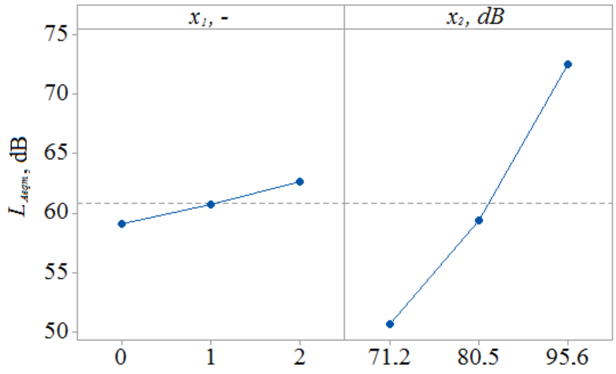

Figure 2. Main effects plot

Taken into consideration this information, a second-order approximating function was generated in the form of Eq. (1). The constant values were calculated and a model was created.

However, it is important to separate the essential and the inessential parts of that equation. That is the reason why significance test was carried out. The result are shown in Table 4.

Table 4. Significance test

Element	Significance
x_1	✓
x_2	✓
x_1^2	X
x_2^2	X
$x_1 \cdot x_2$	✓

Taking the results of the significance test into account, the generated model can be reduced by neglecting the insignificant elements as shown in Eq. (2):

$$L_{Aeq\_int} = -28.94 + 16.04 \cdot x_1 + \\ +1.583 \cdot \mathrm{x}_2 + 0.150 \cdot \mathrm{x}_1^2\text{-}0.0031 \cdot \mathrm{x}_2^2\text{-} \qquad (2)$$

The accuracy of Eq. (2) is illustrated on Figure 3., where the calculated equivalent continuous sound pressure levels of the vehicle interior were plotted against the mean of the measured ones.

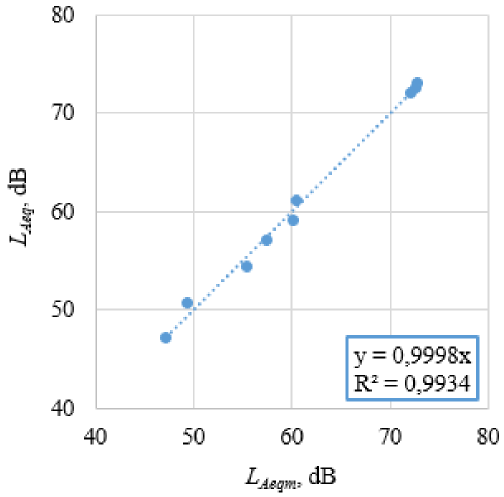

Figure 3. The accuracy of Eq. (2)

If the calculated and the measured values are the same, the graphical representation should be the identity function ($y = x(= 1 \cdot x + 0)$). It can be stated that the equation fitted on the points of Figure 3. is a good approximation of the identity function with a high regression (R^2=0.9934). That means the adequate accuracy of Eq. (2) that is proper to predict the continuous sound pressure level of the vehicle interior in the examined interval of the independent input parameters.

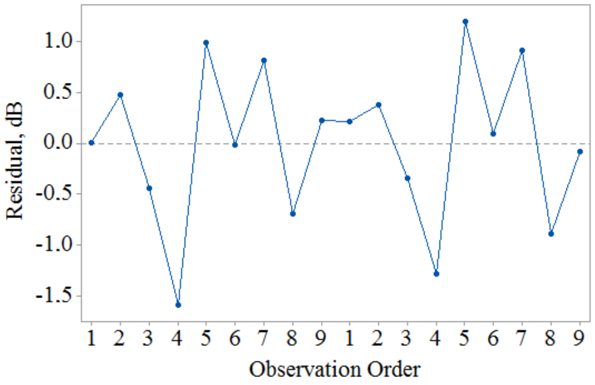

Figure 4. The magnitude of residuals

In addition, the conformity of an empirical equation can be investigated by help of the residuals that are the difference of the measured and calculated values.

Their magnitude is shown on Figure 4.

It can be stated that the values of the residuals are situated in the interval of -1.7…1.2 dB which is a narrow range regarding the measured sound pressure levels in the experimental runs (that means an accuracy of about ±3%).

Furthermore, normality plot, shown in Figure 5. is used to investigate the distribution of the residuals. An empirical model is proper, if the residuals are normal distribution (*P-Value*>0.05), the mean is approximately zero and the value of the standard deviation is low.

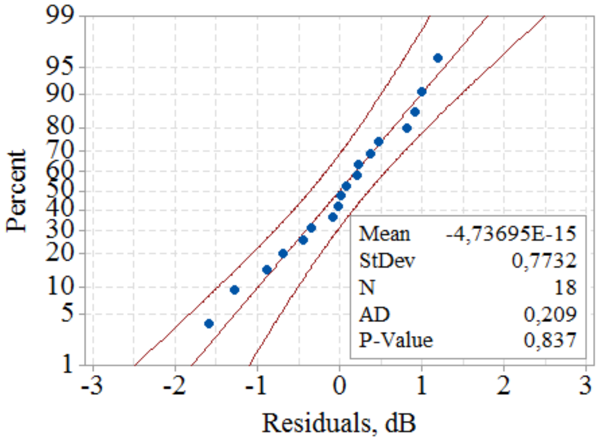

Figure 5. Normality plot

In addition, the range of the residuals was studied It can be stated that their values do not significantly alternate in the investigated interval (see Figure 6.).

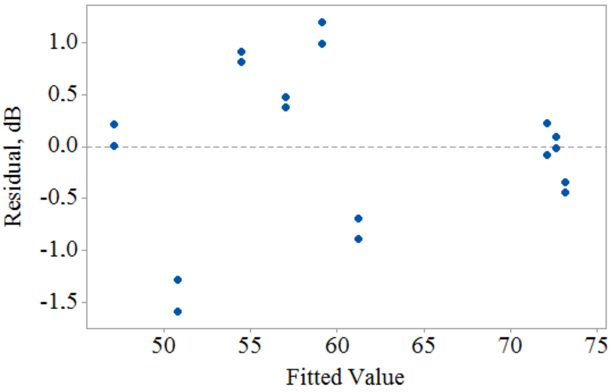

Figure 6. Range of the residuals

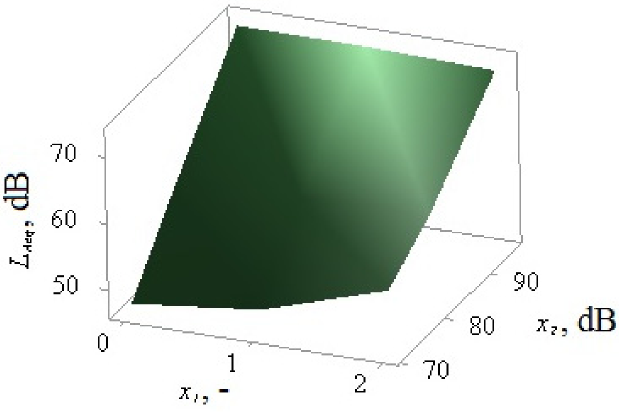

Figure 7. Response surface of L_{Aeq_int}

Having plotted the equivalent continuous sound pressure level of the vehicle interior against the working condition and the external excitation, the graphical representation is a surface shown on Figure 7 . That is proper to investigate the combined effect of the independent variables on the output parameter.

In line with the main effects plot (see Figure 2.), it can be stated that the increased value of both setting parameters results a higher noise level in the vehicle interior. However, in case of the highest external excitation examined the influence of the working condition is less important. That context is more observable on the contour plot shown on Figure 8. which is the projection of L_{Aeq} 1on the x_1-x_2 plane.

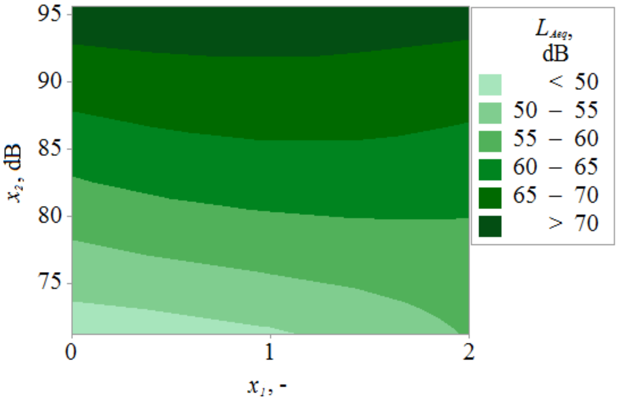

Figure 8. Contour plot of L_{Aeq}

3.4. Confirmation

In order to justify the applicability of the empirical model shown in Eq. (2), further confirming measurements were carried out.

The settings were chosen from the investigated interval of parameters, however, the measurement points differed from the original experimental runs. Table 5. contains the input parameters. In addition, the mean of the measured values and the calculated ones are shown as well.

Table 5. Results of the confirming measurement

Meas. p.	x_1,	x_2,	L_{Aeqm},	L_{Aeq},	ΔL_{Aeq},
	-	dB	dB	dB	%
1	0	83.1	59.9	59.79	0.75
2	1	74.8	53.6	54.00	-0.18
3	2	91.7	69.7	69.26	-0.64

The specific values of the differences between the measured and the calculated results (the difference divided by the measured value) are shown Figure 9 .

According to Figure 9. it can be stated that the generated model shown in Eq. (2) is proper to estimate the equivalent continuous sound pressure level of the vehicle interior with high accuracy in the interval of parameters investigated.

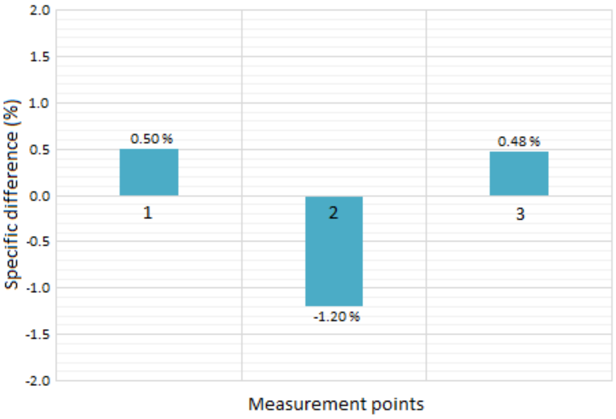

Figure 9. Differences between the measured and the calculated values

4. CONCLUSIONS

In this article, the results of airborne sound measurements were presented. The investigations were carried out on a sample vehicle in an enclosed quiet space.

The equivalent continuous sound pressure level was chosen as dependent variable to characterize the sound quality of the interior. The experimental setup contained the working condition and the external excitation, both having three levels, as input parameters.

Based on the results of the measurements an empirical equation (shown in Eq. (1)) was generated by help of Response surface method. In addition, further significance test was carried out in order to filter the negligible elements. As a result, a reduced model (Eq. (5)) was built that was proper to estimate L_{Aeq} with high accuracy (±3%).

To investigate the conformity of an empirical model, residuals were examined.

The extent of the residuals is in the range of -1.7…1.2 dB which is narrow interval. Furthermore, they follow Gaussian distribution with a mean of approximately zero and a low value of standard deviation. In addition, it can be said that the magnitude of the residuals does not significantly depend on the fitted value.

To sum up, residuals showed that the empirical relationship shown in Eq. (2) is proper to estimate the equivalent continuous sound pressure level of the vehicle interior with an adequate accuracy.

Item, to present the applicability of the model in the whole interval of input parameters examined, further confirming investigations were carried out. The outcome proved that Eq. (2) approaches well the measured results.

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