Acoustic models of bus interior regarding the different points of working combustion engine

The article presents an analysis of sound propagation inside the selected road transport vehicles in the city of Poznan. The research was based on the measurements of the levels of acoustic pressure generated by several bus combustion engines during an acceleration process – at various rotation speed of the crankshaft in combustion engines. Then taking into consideration the measurements and the assumptions of acoustic holography in domain of time, several acoustic models of sound propagation inside the buses at various points on the working combustion engines were elaborated.

Key words: combustion engine, acoustic model, noise, bus

Modele akustyczne wnętrza autobusów w różnych punktach pracy silników spalinowych

W artykule przedstawiono analizę propagacji dźwięku wewnątrz wybranych pojazdów drogowych komunikacji miejskiej miasta Poznań. Przeprowadzono badania polegające na pomiarach ciśnienia akustycznego generowanego przez autobusowe silniki spalinowe w trakcie przyspieszania – przy różnych prędkościach obrotowych wału korbowego silników spalinowych. Następnie na podstawie wyników pomiarów oraz założeń holografii akustycznej w dziedzinie czasu, opracowano modele akustyczne rozkładu poziomu dźwięku wewnątrz autobusów w różnych punktach pracy silników spalinowych.

Słowa kluczowe: silnik spalinowy, model akustyczny, hałas, autobus

1. Introduction

Comfortable conditions of the people transport depend on many factors. One of the most important factor is the noise level generated while the buses are in action. The main sources of raised sound level inside the road vehicles are as follows: work of combustion engine, ride on the bumps on road and the poor technical conditions of the examined technical objects [3]. One can say that the exposition to the biggest values of noise in case of a passenger being in the part of the bus which is close to the place where the engine is situated is relatively higher than in the different parts of this vehicle interior.

On the basis of the main assumptions concerning non-stationary sound field transformation and the measurements of the sound pressure levels generated by the bus combustion engines, several acoustic models of sound propagation were elaborated. The aim of research was to present the distribution of changes in sound levels generated by the combustion engine taking into account the different points of working – in course of a vehicle acceleration and gear shifting. Analysis of these acoustic models allowed to evaluate the instantaneous values of sound level at the different rotation speeds of the combustion engine crankshaft.

2. Research objects

In order to carry out the research, three buses used by MPK Poznan and manufactured by Solaris Bus & Coach were selected. Two of them were the vehicles Urbino 12 No. 1630 and 1634 and one was the vehicle Urbino 18 No. 1870. Combustion engines of these buses generated acoustic signals which were recorded during the measurements. All buses were equipped with a combustion engine whose technical specifications are contained in Table 1.

Vehicles number 1634 and 1870 were equipped with four-speed automatic Voith gearbox codenamed D864 [8] while the vehicle No. 1630 was equipped with a six-speed automatic ZF gearbox codenamed 6 AP 1400B [8]. One of the parameters determining the value of the crankshaft rotation speed in the combustion engine, and thereby the noise level in the vehicle is the mode of driveline (eg. dynamic mode, normal, economic) [8]. Drivelines in all Poznan buses are programmed to act in economic mode.
Table 1. Technical specifications of the tested bus combustion engine [9]

<table>
<thead>
<tr>
<th>Producer</th>
<th>DAF Paccar</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model name</td>
<td>DAF PR229U2</td>
</tr>
<tr>
<td>Type of constru</td>
<td>In-line system, with 6-cylinder, liquid-cooled</td>
</tr>
<tr>
<td>Type of power</td>
<td>Compression ignition unit injector</td>
</tr>
<tr>
<td>Turbocharged</td>
<td>Yes</td>
</tr>
<tr>
<td>Engine cylinder capacity</td>
<td>9186 cm³</td>
</tr>
<tr>
<td>Maximum engine power</td>
<td>228 kW (310 BHP) at a revolution speed 2200 rpm</td>
</tr>
<tr>
<td>Maximum torque of engine</td>
<td>1275 Nm at a revolution speed 1100-1700 rpm</td>
</tr>
<tr>
<td>Compression ratio</td>
<td>17.4:1</td>
</tr>
<tr>
<td>Diameter x Piston stroke</td>
<td>118 mm x 140 mm</td>
</tr>
<tr>
<td>Norm of emission</td>
<td>Euro 5 and EEV (SCR and CRT systems)</td>
</tr>
</tbody>
</table>

3. The methodology of making measurements

Acoustic models of sound level distributions in the bus combustion engines were elaborated on the basis of the measurements of sound pressure which was corrected by A sound frequency characteristic. Three microphones had been processing the acoustic signals during a bus acceleration. The transducers were placed in the rear of the passenger part at a height of 1.6 m [6] – in direct proximity of the engine compartment in vehicle, as shown in Fig. 1. Measurements were made on selected flat section of road with a length of 0.5 km, during acceleration of an empty vehicle. An important factor affecting to the level of noise generated by the combustion engine is the driving style (the way of accelerating). General division of driving styles is into calm and dynamic driving [7].

Measuring equipment used for performing the measurements consisted of the following components:

a) three microphones, Brüel & Kjær Type 4189-L-001, located at the rear of the vehicle (Fig. 1),
b) unit for the fast signal acquisition Brüel & Kjær Type 3560-C Pulse,
c) portable computer (to control and archive the measurement signals).

4. Description of the modeling method

To elaborated acoustic models of the sound levels propagation generated by a combustion engine in function of time, the assumptions of Non-stationary Spatial Transformation of Sound Field method (Non-stationary STSF) [1, 2, 3, 4] was used. The method utilizes holography in the domain of time (so called Time Domain Holography - TDH) [1, 2, 3, 6]. Application of TDH involves the processing of an acoustic signal measured in function of time on the flat surface comprising a sound source [2, 3, 6]. The results of the TDH operation are presented in the form of images (snapshots) arranged in equal time intervals [2, 3, 6] which are shown in Fig. 2.

Fig. 1. Sketch of the rear part interior of the Urbino 12 bus shown in a top view. The digits 1-3 represent the location of microphones. The letters ICE represent the location of the internal combustion engine.
Mathematical interpretation of an acoustic wave propagation in time \( p(x,y,z,t) = p(x,y,z,t) \) is described homogeneous wave equation in space (1) [1, 2, 3, 6]:
\[
\nabla^2 \cdot p - \frac{1}{c^2} \cdot \frac{\partial^2 p}{\partial t^2} = 0
\]
(1)

where:
- \( p \) – acoustic pressure [Pa]
- \( c \) – velocity of sound wave [m/s]
- \( t \) – time [s].

For sound pressure \( p \) there is introduced Fourier transform pair of equations in three dimensions \((x,y,z)\) to coordinate \( z \) according to the equations (2) and (3) [1, 2, 3, 6]:
\[
\begin{align*}
\mathcal{F} \{ p(x,y,z,t) \} & = \frac{1}{(2\pi)^{3/2}} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} p(x,y,z,t) e^{-jk_x x + jk_y y - j\omega t} \, dk_x \, dk_y \, d\omega \\
\mathcal{F}^{-1} \{ P(k_x, k_y, z, \omega) \} & = \frac{1}{(2\pi)^{3/2}} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} e^{jk_x x + jk_y y - j\omega t} \, dx \, dy \, d\omega
\end{align*}
\]
(2)

(3)

where:
- \( p \) – acoustic pressure in function of space and time [Pa]
- \( P \) – sound pressure in frequency domains of time and space [Pa]
- \( k \) – wave number
- \( \omega \) – the frequency of the acoustic signal [rad/s].

Noise maps were elaborated with use the NoiseAtWork software. In order to implement the acoustic models, the noise maps were ranked in the correct order and equal interval of 0.2 s. Additionally, the soundtracks processed by the microphones which are located closest to the engine compartment (microphones No. 1) were attached to the models.

5. The modeling results

During the research, three acoustic models of the distribution of sound levels inside the selected buses at various points of the combustion engines in action were performed. In the article will be presented the analysis of the models during the acceleration of a bus and gear shifting.

The first model presents the distribution of acoustic noise inside the bus Solaris Urbino 12 No. 1634. Fig. 3 shows the six one after the other ranked noise maps presenting the distribution of sound levels which were changed themselves during the process of acceleration of the vehicle on the first gear ratio and the gear change from the first to the second. The instantaneous sound level recorded by microphone No. 1 on the first noise map was equal of 75 dB. At that time speed of the engine crankshaft was equal of 600 rpm (it is speed of the engine crankshaft idling). The acceleration process with the first gear of the vehicle is presented on the next two noise maps (Fig. 3 No. 1, 2). The rotation speed of crankshaft engine increased up to 1500 rpm value with an increase in the value of the instantaneous sound level up to 83 dB - recorded by a microphone No. 1. The last three noise maps (Fig 3 No. 4, 5, 6) illustrate the process of automatic gear shifting from first to second. At that moment one could observe the decrease in the value of instantaneous sound level down to about 78 dB. At the
same time it could be found the decrease in the value of instantaneous speed of the engine crankshaft down to 600 rpm. Fig. 5 shows the characteristic of changing in instantaneous sound level inside the vehicle as a function of time. On the basis of this analysis it can conclude that the vehicle accelerates on first gear by two seconds while the process of changing the gear lasted just over one second. Fig. 4 presents the range of colors matched along with the ranges of sound levels corrected by the frequency response A. The difference in the instantaneous sound levels between the first and third microphone was about 3-4 dB. The distance between the outermost microphones was the equal of 2.5 m.

Fig. 3. Acoustic maps showing the changing in distribution of sound pressure levels during the process of acceleration and gear shifting from the first to the second in the Solaris Urbino 12 no. 1634

Fig. 4. Range of colors matched along with assigned sound pressure levels A

Fig. 5. Changing in sound pressure level during an acceleration of the vehicle no. 1634 and the gear shifting from the first to the second in function of time
Next acoustic model presents the changing of sound levels inside the bus Solaris Urbino 12 No. 1630 during an acceleration and gear shifting from the fourth to the fifth gear (Fig. 6). The vehicle is equipped with the same type of combustion engine, but has six-speed ZF gearbox. With more gear ratios there is frequent gear shifts. It means that the rotation speed of the engine crankshaft is lower, which affects the generated sound level. On the first noise map in Fig. 6 we can find a low instantaneous sound level of 78 dB which is recorded by microphone No. 1. The reason for that level it is the low value of the rotation speed of the crankshaft engine. Next the vehicle has accelerated in fourth gear. It causes an increase in the rotation speed of the crankshaft engine up to about 1200 rpm and raises the instantaneous sound level up to 82 dB; it is presented on the fourth noise map on Fig. 6. The last two noise maps show a sudden drop in the value of the instantaneous sound level down to 79 dB. The reason for the decrease of noise inside the vehicle is automatic shifting from the fourth to the fifth gear. Range of colors matched along with the ranges of sound levels corrected by frequency response A are the same for every model (Fig. 4). The vehicle acceleration and gear shift process in the bus lasted more than three seconds (Fig. 7). In the same time the velocity of vehicle has increased from about 25 km/h to less than 40 km/h. Also in this case the difference between the instantaneous sound levels and the positions of microphones were the same as in the first acoustic model.

![Fig. 6. Acoustic maps showing the change in distribution of sound pressure levels during the process of an acceleration and gear shifting from the fourth to the fifth in the Solaris Urbino 12 no. 1630](image)

![Fig. 7. Changing in sound pressure level during the vehicle no. 1630 acceleration and gear shifting from the fourth to the fifth in function of time](image)

The lastly elaborated acoustic model presents the changes in the instantaneous sound levels inside the Solaris Urbino 18 No. 1870 during the vehicle acceleration with second gear and automatic shifting to the third gear. The vehicle is equipped with DAF combustion engine and four-speed Voith
gearbox. Fig. 8 presents six following noise maps. First noise map indicates the value of the instantaneous sound level recorded by the microphone No. 1 which amounts to 77 dB. The reason for the noise decreasing is lower rotation speed of the crankshaft engine. The next noise maps show the growth of instantaneous sound levels up to about 82 dB. It is due to the increase in the rotation speed of the engine crankshaft up to about 1200 rpm. At that moment the automatic shifting from second to third gear was done. Simultaneously, it can be found a decrease in rotation speed of the engine crankshaft and in noise down to less than 79 dB. Fig. 9 shows a process of changing in instantaneous sound pressure levels during an acceleration as a function of time. Within four seconds the bus velocity increased by 10 km/h.

The difference in the instantaneous sound pressure levels recorded by two outermost microphones was around 3-4 dB. The distance between them is more than 3 m.

6. Summary and conclusions

The instantaneous sound pressure levels depend on the rotation speed of the crankshaft combustion engine. The analysis of the research has shown that the highest values of the instantaneous sound pressure levels were approximately of 82-83 dB (recorded by microphone No. 1) with the value of rotation speed of the crankshaft engine about 1500 rpm. While the lowest sound values are about 77-78 dB (recorded by microphone No. 3) at 600 rpm of rotation speed of the crankshaft combustion engine during the process of gear shifting. The difference between two outermost microphones in all cases was 3-4 dB.

The noise level generated by the combustion engine located at the rear part of buses depends on many factors. The most important of them are: vehicle load, landform features, driving style and mode of driveline. In the research on its results the driving style had the greatest significance. It can be
found that the more dynamic driving style (faster acceleration of a vehicle, higher rotation speeds of the engine crankshaft) means the greater noise inside the bus. Furthermore, the combustion engines were placed in the compartments separating them from passenger space what further affect the attenuation of the acoustic waves.

**Bibliography/Literatura**


[7] Technical data obtained from MPK Poznan Sp. z o.o. based on tests performed by the carrier.
