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ATMOSPHERIC AND AEROACOUSTICS

Buffeting-Noise Evaluation in Passenger Vehicle BMV 530d

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Abstract—In this paper we exhibit the results and evaluation of the buffeting-noise effect in a BMW 530d model vehicle. The buffeting noise was studied in real measurement conditions in an outdoors highway at different speeds. We evaluate different listening positions inside the vehicle to demonstrate that the buffeting-noise effect is independent from the listener position.

Keywords: buffeting noise, car, listener position
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INTRODUCTION

Passenger comfort is extremely important in public transport as well as private. This comfort is characterized, for example, by illumination, temperature, pressure, and sounds and vibrations. In all vehicles, noises may be generated by the engine, train and road excitation, and wind fluctuations. Modern passenger vehicles are designed to reduce almost all maximum external and mechanical noises. New vehicle design and the mechanical technology improvements make noise reduction possible. Cavity design is applied to make the vehicle more user-friendly, comfortable, and secure. The outer surface of the vehicle aims at giving off an image of luxury, as well as increasing vehicle speed and power. Nevertheless, an important characteristic that cannot be reduced is buffeting noise, that is, noises generated in the vehicle cavity when the rear windows are opened.

Driving with lateral windows open at high speed generates a pulsating noise named buffeting noise [1]. These buffeting noises are quasistationary broadband signals generated by aerodynamic turbulence. The human ear is unable to hear the above-mentioned low-frequency and high-intensity noises. Nevertheless, these sounds contribute to the discomfort of the passengers [2]. Due to the fact that low-frequency noises are not audible by the human ear, inside a vehicle, they pressure the human body and external ear [3, 4].

The effect of buffeting/aerodynamic noises generates fatigue and anxiety in vehicle occupants. Reference [5] demonstrated that buffeting noises are mostly generated in open rear windows. There are, however, cases when buffeting noise is generated with open front windows.

Early studies on buffeting noises had the objective to characterize the effect of buffeting noise. Lately, research has focused on the development of computer-simulation techniques [6–8]. Nowadays, methods used to study buffeting noises are theoretical and experimental, and simulation analyses [9]. Actual technologies can now realize computer simulations as a PAM-FLOW [2]. The simulation techniques applied in buffeting-noise analysis are based on fluid mechanics, and include visualization techniques with Particle Image Velometry [10–12].

The research on reducing the effect of buffeting noise is based on tunnel testing [13]. This research is a high-cost experiment and does not analyze the conditions of real turbulence produced by other vehicles, nor the continuous change of environmental airflow.

This paper analyses the existence of airflow regions in vehicles and studies how these regions affect buffeting-noise generation.

It is important to mention that three airflow regions exist. The first region generates a spiral airflow. Analyzed, it has been shown to move on the top part of the side windows. The top region or the first region starts with the formation of an A-pillar vortex. According to speed, this vortex grows in size. This fact corroborates contributes to easier buffeting-noise generation. The flow around a turbulent is precisely can be associated with the formation of aeroacoustic resonances.

The Von Karman vortex flow is the result of inserting an object in the airflow path. This type of airflow region is the second region. In vehicles, the presence of the side mirrors generates this effect [14, 15], generating an area behind them. The vortices become greater, having a considerable size when passing through the vehicle rear windows, contributing to buffeting-noise generation. The effect increases when the side window is open more than halfway down.

The third and final region is the middle region or reattached flow. In this region, airflow is generated in a cylindrical vortex. It is generated due to the presence of the edge of the windshield on the airflow path. Buffeting noise is also called cavity noise, which is composed of two components: random and periodic.

EXPERIMENTS

For buffeting-noise effect characterization, we used a BMW 530d model. The vehicle was experimented on in real conditions, free of traffic roads.

Different speed intervals were analyzed in this work. Speed intervals increased by 10 km/h. The minimum analyzed speed was 60 km/h, and the maximum speed was 120 km/h due to the road speed limitations. In the study, the effect of buffeting noise, with open front and rear windows, was analyzed [8, 11, 16, 17]. Each vehicle was tested three times in different traffic conditions at seven speeds. Stimuli were recorded with professional equipment placed on the copilot seat.

RESULTS AND DISCUSSIONS

Figure 2 presents the results from a fully open left- and right-rear window of a BMW 530d model vehicle. In the present experiment, the increase of buffeting noises during the experiment and velocity are presented. Frequency $f = 20.3$ Hz.

As shown in Fig. 2 buffeting noise increases on the left-rear window opened from 60 to 110 km/h, then it decreases. Nevertheless, when the right-rear window is fully open, buffeting noise begins to increases from 70 km/h. At 60 km/h, the Sound Pressure Level (*SPL*) was already at 96 dB. The maximum *SPL* value for the left-rear window was achieved at 110 km/h, and for the right-rear window at 120 km/h.

Figure 3 indicates that, at low speed, the sound-pressure level is low. At 14.8 Hz the buffeting noise achieves 117.7 dB. From 60 to 110 km/h, the *SPL* increases exponentially. A large difference is perceived in the dependence of the *SPL* and frequency regarding 120 km/h velocity. This demonstrates that maximum $SPL = 122.5$ dB is achieved at $f = 21.9$ Hz and 129 km/h. From the presented measurements, it is observed that Helmholtz resonance increases with increasing speed in the interior of the vehicle for the left-rear window totally opened.

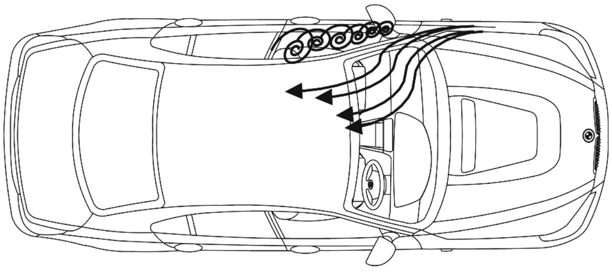

Fig. 1. Formation of the A-pillar vortex.

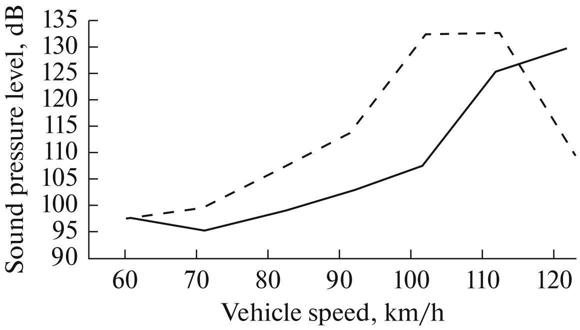

Fig. 2. BMW 530d model vehicle results of the *SPL* measurements at frequency $f = 20.3$ Hz for left- and right-rear open window. The dotted line shows *SPL* variation for fully open left-rear window and continuous line indicates the evolution of the right rear window fully opened. The front left seat was occupied by the driver.

SPL fluctuation in the frequency domain has been measured in real driving conditions at different speeds. Figure 4 presents the fluctuations of the *SPL* when the front-right window is fully opened with the microphone in the back seat of the vehicle.

In general, in the interval from 0 to 25 Hz, no important fluctuations on the *SPL* were perceived. At 60 and 90 km/h, some small fluctuations were registered. In order to perceive if the BMW 530d model generates fluctuations on the frequency domain, an experiment was conducted at 60 km/h speed. Figure 5 displays the experimental results in real conditions. The main peak of *SPL* fluctuation was at 10.9 Hz, while other peaks were small and insignificant. These clear perceived fluctuations define instability in the vehicle cabin. They represent the fundamental frequency on wind noises or the buffeting noise for 60 km/h velocity. The fluctuations that describe the buffeting noise can be defined as an aeroacoustic feedback loop generated by airflow at high speed. When the air vortex appears on the vehicle cabin, it generates a cavity resonance called the Helmholtz resonance [18].

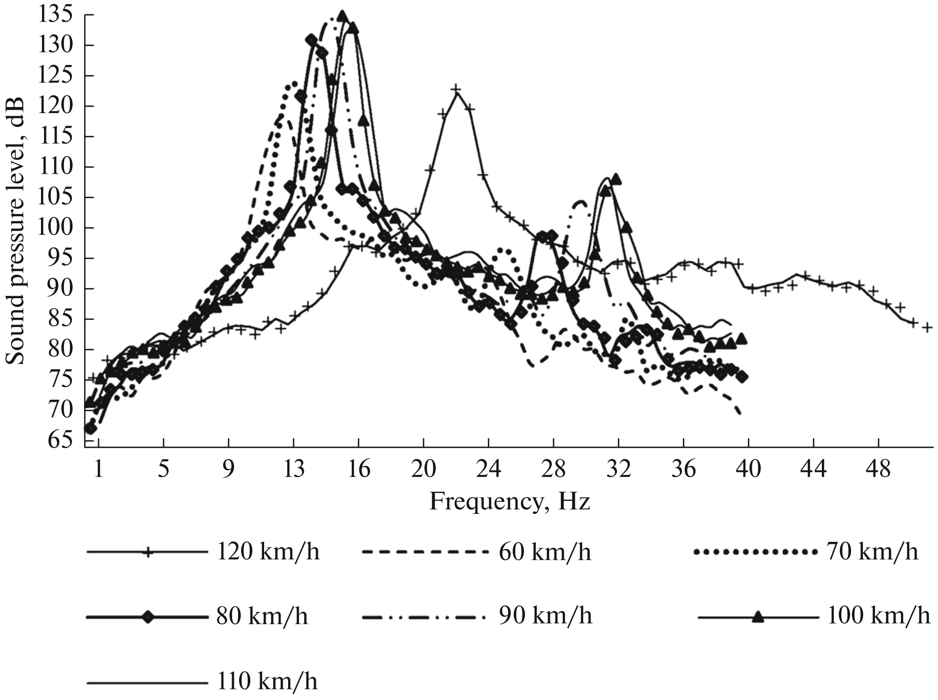

Fig. 3. Sound Pressure Level (*SPL*) measurements of frequency variable for open left-rear window with several speeds.

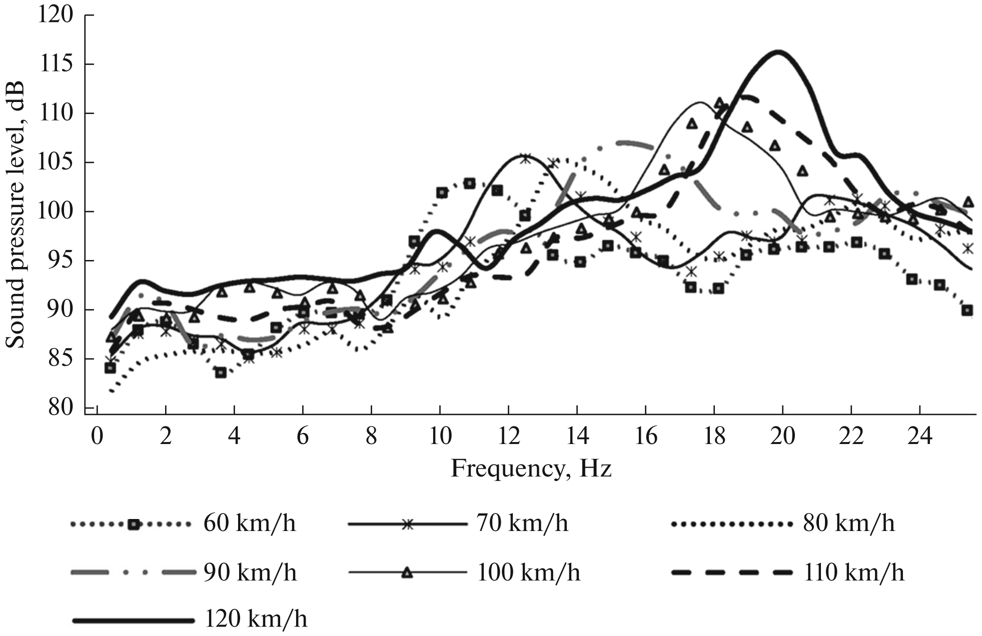

Fig. 4. BMW 530d model. Front-right window fully opened with the microphone in the back seat of the vehicle. The measurements were recorded for different velocities, from 60 to 120 km/h, for different frequencies.

From Fig. 3 it can also be observed that *SPL* fluctuations appear twice, from 80 to 110 km/h at a frequency from 24 to 32 Hz.

Sound-pressure level affects positions of the vehicle differently. The design of the vehicle is mainly based on limitations of sound-pressure level in the vehicle cabin. At certain vehicle locations, buffeting noises affect passengers differently. The presented case is realized in conditions when the left-back window is totally opened. The experiment was done in an open environment in a real highway without traffic. Figure 6 and Table 1 represent the results of sound-

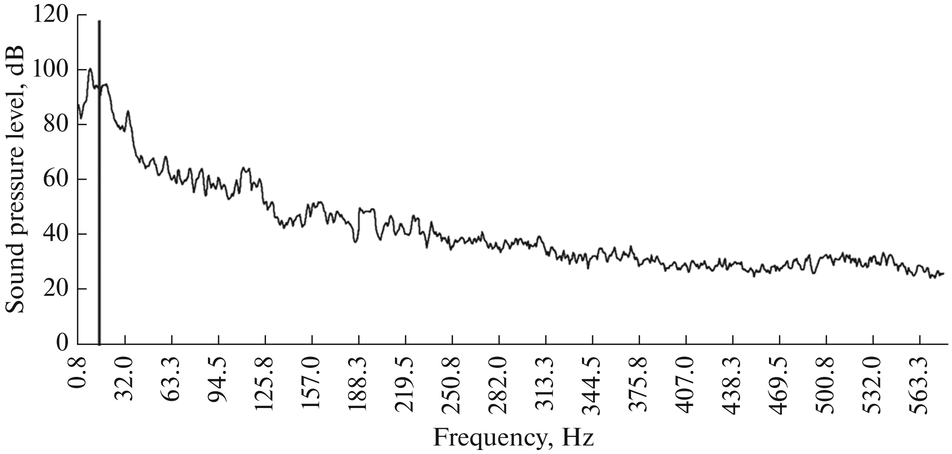

Fig. 5. Sound-pressure level at receiver location. Front-right window fully opened with the microphone in the back seat of the vehicle. Measurements were recorded for the 60 km/h velocity in frequency domain.

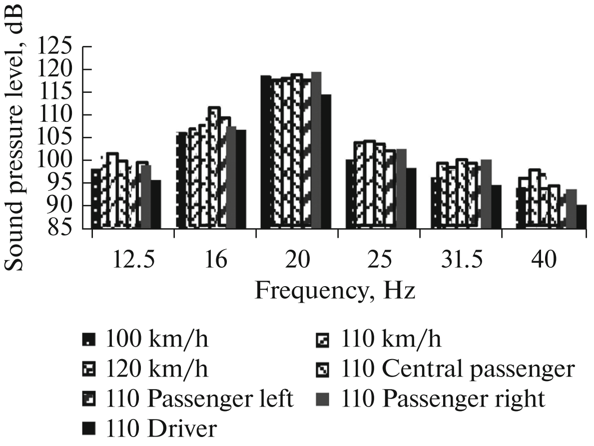

Fig. 6. Sound-pressure level at receiver location.

pressure level for 100, 110, and 120 km/h, and also the *SPL* measurements for 110 km/h at different positions of the microphone inside the vehicle.

From the present measurements, it can be observed that, on the driver position, the *SPL* is lower compared to the microphone's other positions. The *SPL* is lower, with a minimum of 2 dB, and achieves a difference of 7 dB.

Regarding the obtained result, it can be observed that the *SPL* actually varies depending on velocity, frequency, and the percentage of the opened window. In the present study, we conclude that the buffeting noise in the BMW 530d model vehicle occurs for frequencies lower than 20 Hz.

In Reference [19], the authors analyzed the buffeting noises for different vehicle models at different speeds in real conditions. As mentioned [20–22], buffeting noises generated at low frequencies are not perceived by the human ear, but are perceived as a pulsating wind force over the body and ear. These pulsations irritate and fatigue passengers.

At a frequency of 12.5 Hz, a reduction of sound-pressure level was perceived. The highest *SPL* was perceived in the central back seat and the front-right seat.

From the above results, we can see that the reduction of buffeting noises when the rear window is fully opened is required. The solution is to create an

Table 1. Sound-pressure level, dB for different positions of the recorder at 110 km/h, and comparative data from 100 to 120 km/h

	Sound Pressure Level (*SPL*), dB						
F, Hz	100 km/h	110 km/h	120 km/h	110 km/h central back micro	110 km/h pass L	110 km/h pass R	110 km/h driver
12.5	98.2	**101**	99.3	97.8	**99.1**	99	95.8
16	106.2	106.5	**107.3**	**111.2**	108.9	107.4	106.7
20	**118.5**	117.3	117.9	118.6	117.4	**119.2**	114.3
25	100.3	103.4	**103.7**	**103.1**	101.7	102.5	98.5
31.5	96.4	**98.9**	98	99.6	98.9	**100.3**	94.7

escaped trajectory inside the vehicle. This trajectory would absorb airflow inside the vehicle. It is possible that the combination of opened front and rear windows decreases buffeting noises [23, 24, 19].

CONCLUSIONS

This work studies buffeting noises on a BMW 530d vehicle. When frequency is less than 20 Hz, the passengers perceive airflow inside the vehicle as pulsating noises. These noises are very important for passengers' comfort. This work evaluated buffeting noise and its characteristics for velocities from 60 to 120 km/h due to the speed limits in the highway. The amplitude of the buffeting noise was measured for different positions of the microphone inside the vehicle, with different frequencies and speeds. The results clearly demonstrate that, in the frequency range of 10 to 40 dB, buffeting noises occur inside the vehicle at all speeds.

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