euronoise
Naples 2003

Theoretical and experimental investigation of the aerodynamic noise generated by air flows through car windows

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Motor vehicle aerodynamic noise characteristics have been investigated. A vehicle driver may be particularly annoyed at open-windows conditions. Thus, a measurement campaign has been carried out in order to characterize the aerodynamic noise generated by air flows through vehicle windows. Noise levels have been measured at the driver ears by varying vehicle speed and driver-side window opened area. Measurements results have shown that main noise component frequencies values depends on the following physical parameters: vehicle speed, car internal volume, window opened surface. Such results agree with the Helmoltz theory which has been employed to model the vehicle internal noise. A simple equation to evaluate global internal noise has been proposed. Estimated noise level values are very close to the experimental ones.

1. INTRODUCTION

Motor vehicle internal noise is due to the following sources:
a) exhaust duct noise;
b) engine and mechanical structures vibrations;
c) rolling tyres noise;
d) aerodynamic friction.

Exhaust noise may be reduced by means of multi-stage passive mufflers; active noise control mufflers may be also introduced to improve low frequency abatement [1]. Low noise emission engines and sound insulation cowlings make contribute b) the lowest one; rolling noise is contrasted by means of sound absorbing pavements and an appropriate design of tyre shape [2]. Aerodynamic noise may be reduced by peculiar vehicle shape design [3]; however, aerodynamic noise is particularly remarkable when vehicle windows are opened. A measurement campaign has been led to evaluate aerodynamic noise characteristics at open-windows conditions. Two commercial car have been tested. Measurement conditions have been chosen to minimize a), b) and c) contributes with respect to the d) one. Noise levels have been measured near driver ears for different window opening conditions and vehicle velocities. Measurements results have shown noise power is distributed in a very low frequency range. Main component frequency increases with windows opened area complying Helmoltz theory. By theoretical and experimental results a simple model for evaluating vehicle internal noise level has been introduced.

2. MEASUREMENT METHOD

Noise levels at opened windows conditions have been determined. Measurement equipment is made up by a Bruel & Kjaer Investigator 2260 phonometer with Bruel & Kjaer model 4189 microphone. Measurements have been carried out inside two commercial cars, equipped with different shape windows: 1) Fiat Bravo 1.5 SX; 2) Volkswagen Passat Limousine TDI. Aerodynamic noise measurements have been led under the following conditions in order to minimize a), b) and c) car noise contributes(see introduction):

1) slightly-downward street and gears set on neutral position (low a) contribute);
2) insulating cowlings (low b) contribute);
3) silent tyres (low c) contribute);

Tests have been carried out for different driver-side window opened area and vehicle velocity conditions. Measurement microphone has been equipped with a windscreen protection and has been positioned near the window-side driver ear (see Figure 1).

Figure 1: *measurement microphone position*

3. MEASUREMENT RESULTS

Aerodynamic noise levels relative to different vehicle speed and window opening conditions are reported in Table 1 which have been determined by subtracting noise contributes measured in closed window conditions to the noise levels measured in opened window conditions. Aerodynamic noise L_{Leq} values increase with vehicle speed and window opened area. Figure 2 shows aerodynamic noise spectra for the following extreme conditions:

- ¾ closed window, 40 km/h speed (Car 1);
- opened window, 140 km/h speed (Car 1).

Different combinations of window opened area and vehicle speed produce noise spectra which are included within the previous extreme conditions. Measurement results have shown that noise power is mainly distributed in (16-31.5) Hz frequency range.

Main noise components (MNC) frequency values versus window opening conditions are reported in Table 2. MNC frequencies are insensitive of vehicle speed; it makes suppose that car internal volume and window opened area comply Helmoltz theory [4]. This fact occurs for each kind of vehicle.

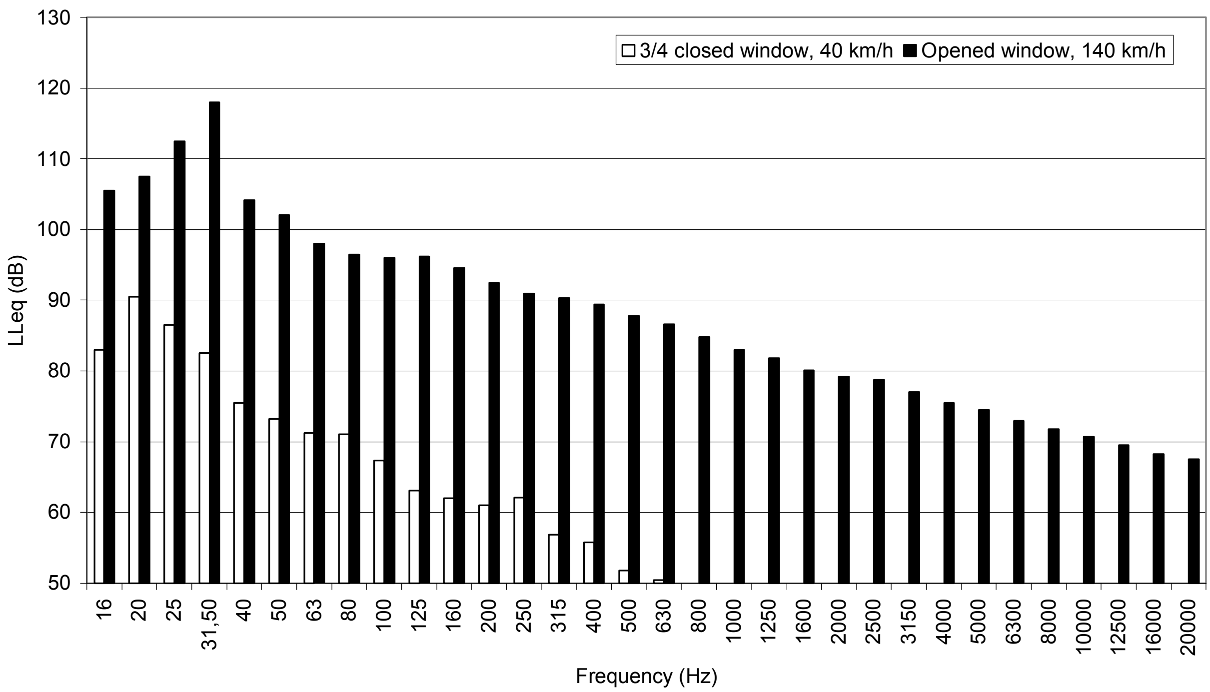

Figure 2: *measured aerodynamic noise spectra relative to car 1 (window opened area and vehicle speed extreme conditions)*

4. THEORETICAL DISCUSSION OF THE EXPERIMENTAL RESULTS

Vehicle internal volume and window opened surface are assimilable to an Helmoltz resonator. Resonance frequency f_r which characterizes car driver perceived noise at open window conditions may be calculated as [5]:

$$f_r = \frac{c}{2 \cdot \pi} \sqrt{\frac{A}{V \cdot \left(h + \frac{8D_{eq}}{3\pi} \right)}} \qquad (1)$$

D_{eq} is the diameter of a circular shape window the area of which is equivalent to the effective one. Vehicle geometrical characteristics and Helmoltz resonance frequency are reported in Table 2 for each vehicle-window combination.

Calculated resonance frequencies are very close to the MNC ones which have been individuated by means of the experimental campaign.

Table 1: *Measured and estimated aerodynamic noise (AN) levels*

Window Condition	***Vehicle Speed (Km/h)***	***Car 1 (Fiat Bravo)***			***Car 2 (Volkswagen Passat)***		
		Measured AN L_{Leq} (dB)	***Estimated AN L_p (dB)***	***Δ (dB)***	***Measured AN L_{Leq} (dB)***	***Estimated AN L_p (dB)***	***Δ (dB)***
Opened	*40*	99.5	101.8	-2.3	99.0	99.6	-0.6
	60	108.5	108.8	-0.3	106.5	106.7	-0.2
	80	114.5	113.2	+1.3	113.0	111.1	+1.9
	100	117.0	116.3	+0.7	116.0	114.2	+1.8
	120	118.5	118.8	-0.3	117.0	116.7	+0.3
	140	120.0	120.8	-0.8	118.5	118.7	-0.2
¼ Closed	*40*	98.0	99.3	-1.3	96.5	97.1	-0.6
	60	104.5	106.3	-1.8	102.5	104.2	-1.7
	80	111.0	110.7	+0.3	109.0	108.6	+0.4
	100	114.0	113.9	+0.1	112.5	111.7	+0.8
	120	115.0	116.3	-1.3	113.5	114.2	-0.7
	140	116.5	118.3	-1.8	115.0	116.2	-1.2
½ Closed	*40*	95.5	95.7	-0.2	93.0	93.6	-0.6
	60	100.0	102.8	-2.8	98.5	100.7	-2.2
	80	105.0	107.2	-2.2	105.0	105.1	-0.1
	100	110.0	110.3	-0.3	109.0	108.2	+0.8
	120	112.0	112.8	-0.8	110.5	110.7	-0.2
	140	114.0	114.8	-0.8	112.0	112.7	-0.7
¾ Closed	*40*	93.0	89.7	+3.3	90.0	87.6	+2.4
	60	95.5	96.8	-1.3	94.5	94.7	-0.2
	80	103.0	101.2	+1.8	102.0	99.1	+2.9
	100	107.0	104.3	+2.7	105.0	102.2	+2.8
	120	108.5	106.8	+1.7	106.5	104.7	+1.8
	140	109.0	108.8	+0.2	108.0	106.7	+1.3

By Table 1 aerodynamic noise sound pressure depends on vehicle speed and window opening conditions according respectively to a logarithmic and a linear relation. Vehicle internal volume affects only noise spectra distribution.
A simple model has been proposed to evaluate aerodynamic noise pressure level:

$$L_p = 10\log_{10}\left[\frac{K \cdot A \cdot v_v \cdot \ln\left(\frac{v_v}{v_0}\right)}{p_0}\right]^2 \qquad (2)$$

where v_0 is a vehicle speed reference value (equal to 5m/s for all the vehicle-window configurations). K is a parameter depending on the vehicle window shape. It has been determined by a calibration measurement. K values are 0.8 $m^4/kg \cdot s$ and 0.7 $m^4/kg \cdot s$ respectively for car 1 and 2. Aerodynamic noise estimated levels are reported in Table 1. Calculated values are very close to the measured ones (car 1 and 2 average estimation relative error equal respectively to 1.27% and 1.10%).

Table 2: A*erodynamic noise MNC frequency values by means of measurement results and Helmoltz theory*

Vehicle	*Window Conditions*	*A* *(m^2)*	*D_{eq}* *(m)*	*h* *(m)*	*V* *(m^3)*	*f_r* *(Hz)*	*Measured MNC* *(Hz)*
1	*opened*	0.3451	0.6629	0.0030	2.1	29.4	31.5
	¼ closed	0.2588	0.5741			27.4	within 25-31.5 Hz range
	½ closed	0.1726	0.4687			24.7	25
	¾ closed	0.0863	0.3314			20.7	20
2	*opened*	0.3094	0.6279	0.0030	2.8	24.8	25
	¼ closed	0.2321	0.5436			23.0	within 20-25 Hz range
	½ closed	0.1547	0.4438			20.8	20
	¾ closed	0.0774	0.3138			17.5	within 16-20 Hz range

5. CONCLUSIONS

An experimental investigation on aerodynamic noise perceived by car drivers in open-windows conditions has been carried out. A measurements campaign has been led by varying vehicle speed and driver-side window opened area.

Aerodynamic noise spectra show very low main noise components (MNC) distributed in 16-31.5 Hz range. MNC frequency increases with vehicle window opened area. Vehicle internal volume and window opened surface have been assimilated to an Helmoltz resonator; it has been found out that MNC frequency is very close to Helmoltz resonator frequency for each vehicle speed and window opening conditions. Furthermore, MNC levels depend on window opening area and car velocity respectively according to a linear and a logarithmic law.

This fact has allowed to introduce a simple relation which may be employed to estimate opened window car internal noise. The proposed relation will also be employed to individuate an annoyance index for car drivers.

6. TABLE OF SYMBOLS

Symbol	Units	Description
A	m^2	window opened area
c	$m \cdot s^{-1}$	sound velocity
D_{eq}	m	equivalent diameter of the window opened surface
Δ	dB	difference between measured and estimated noise levels
h	m	window thickness
K	$m^4/kg \cdot s$	evaluation model calibration constant
L_{Leq}	dB	equivalent noise level
L_p	dB	pressure level
p_0	Pa	pressure reference value
V	m^3	vehicle internal volume
v_0	$m \cdot s^{-1}$	vehicle speed reference value
v_v	$m \cdot s^{-1}$	vehicle speed

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