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SQUEAKING NOISE PSYCHOACOUSTIC EVALUATION FOR CAR PASSENGERS

Federico Rossi and Andrea Nicolini[1]

[1]University of Perugia – Industrial Engineering Department
Via G. Duranti 67, 06125, Perugia, Italy
frossi@unipg.it

Abstract

This paper deals with the proposal of evaluation indexes of annoyance and pleasantness due to squeaking noises in vehicle cabins. Indexes represent the average sensation of a S.A.O. (Statistical Average Observer) which was subjected to a jury test. The investigation was carried out by these following main steps: a measurement campaign conducted to record squeaking noise signals near the passenger's hearing position; an objective analysis to evaluate psychoacoustic metrics for each squeaking noise signal; a jury test to detect annoyance and pleasantness due to each noise signal by a Semantic Differential and Pair Comparison methods [1, 2]. At last, psychoacoustic indexes were found by regressive analysis. Indexes correlate "No annoyance" and "Pleasantness" to the psychoacoustic metrics.

1. INTRODUCTION

Acoustic comfort inside vehicle cabins is made up by many factors: vibrations, shocks, accelerations and decelerations, engine noise, cabin acoustic insulation, rolling noise. Squeaking and rattling noises are often responsible of acoustic discomfort. They may be generated by many causes: mechanical adjustment of seats, setting of instrument panel drive grips, safety belts hook/unhook, etc. However, it may be very difficult to assess the discomfort due to these noises. Rattling noises were analysed in a previous paper and an index for "No annoyance" and "Pleasantness" evaluation was proposed [3]. Annoyance and pleasantness of vehicle passengers due to squeaking noises is investigated here. The investigation was carried out by a measurement campaign, a physical analysis of the measurement results and a jury test by a Statistical Average Observer (S.A.O.). Psychoacoustic single number indexes depending on loudness and sharpness metrics were found by a regressive analysis.

2. THE MEASUREMENT CAMPAIGN

A measurement campaign was led by a test bench and a test head for binaural recordings at CRF (Centro Ricerche Fiat - Turin – Italy) thanks to an agreement between FIAT Auto S.p.a. and University of Perugia. Recordings were checked in order to detect squeaking noise signals due to mechanical and structural vehicle components. 25 squeaking noise signals were found. Each signal is an average 2 seconds long. The selected noises were caused by routine activities usually occurring in the passenger cars or by drivers, such as setting the air conditioner grip (n.1 to n.13 signals), or squeaking the carpet with the vehicle pavement (n.14 to n.25 signals). Figures 1-2 report typical time behaviour and average spectrum of the investigated squeaking noises. It is shown and verified for each signal that squeaking noises are characterized by a monotonic decreasing spectrum with a main component in the low frequency range (100-200 Hz).

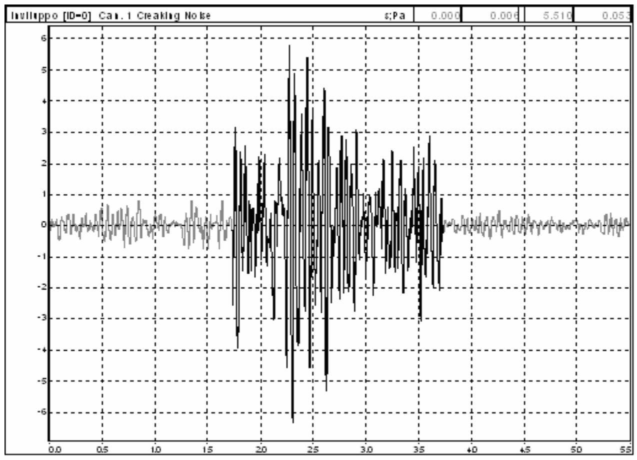

Figure 1. Squeaking noise typical time behaviour (referred to n.16 squeaking signal)

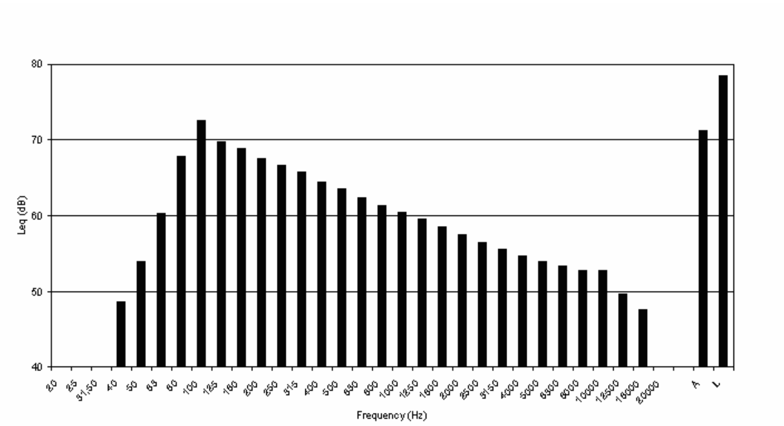

Figure 2. Squeaking noise typical spectrum (referred to n.16 squeaking signal)

3. THE PSYCHOACOUSTIC EVALUATION

The adopted methodology for psychoacoustic evaluation is based on two main phases:

- objective analyses by a numerical code;
- jury test by a S.A.O. using binaural headphones (subjective analyses).

The correlation between the objective and the subjective analyses allowed to obtain relations between psychoacoustic metrics; the obtained relations allowed to predict “No annoyance” and “Pleasantness” due to squeaking noises only by objective analyses.

Psychoacoustics metrics were evaluated by the objective analysis using a numerical code: stationary loudness, roughness, fluctuation strength, statistical loudness and instantaneous loudness statistical Zwicker sharpness, statistical Aures sharpness in terms of mean, maximum and minimum values, standard deviation, 5, 10, 50 and 90 percentiles [4, 5]. Results are shown in Table 1 (only the metrics useful for the following analyses are reported for brevity).

Table 1. Psychoacoustic metrics values for squeaking noises

Metric	*Squeaking noise (Reference number)*								
	1	2	3	4	5	6	7	8	9
R (asper)	2.02	2.27	2.84	2.74	2.61	2.39	2.52	2.52	2.41
F (vacil)	2.02	2.91	2.84	2.78	2.61	2.82	2.75	2.52	2.33
N_{max} (sone)	7.78	7.86	10.56	7.85	9.09	8.46	10.24	9.77	8.93
N_M (sone)	3.68	3.93	4.46	4.04	3.58	4.06	4.27	5.05	4.23
N_σ (sone)	1.71	1.81	2.26	1.96	1.81	2.00	2.10	2.22	2.10
N_5 (sone)	6.89	7.41	8.23	7.45	6.94	7.91	7.95	8.52	7.96
S_{ZwM} (acum)	1.13	1.10	1.09	1.11	1.14	1.12	1.08	1.04	1.10
S_{Aumax} (acum)	2.55	2.60	2.65	1.86	2.39	2.63	2.84	2.46	2.52
Metric	*Squeaking noise (Reference number)*								
	10	11	12	13	14	15	16	17	18
R (asper)	2.63	2.16	2.93	2.50	3.79	4.60	3.73	3.91	2.90
F (vacil)	2.63	2.16	3.65	2.50	2.56	4.60	3.73	2.58	2.90
N_{max} (sone)	12.95	9.22	10.57	8.05	11.94	14.73	12.50	9.48	10.43
N_M (sone)	5.13	2.90	5.36	2.92	3.98	5.45	4.50	4.05	4.25
N_σ (sone)	2.75	1.16	2.08	1.08	2.18	3.68	2.36	1.92	2.10
N_5 (sone)	11.14	3.34	7.89	3.71	7.42	12.01	8.86	7.71	9.11
S_{ZwM} (acum)	1.06	1.22	1.00	1.21	1.08	1.07	1.07	1.08	0.17
S_{Aumax} (acum)	2.99	2.14	2.57	2.14	2.23	2.91	3.20	2.44	3.14
Metric	*Squeaking noise (Reference number)*								
	19	20	21	22	23	24	25		
R (asper)	2.51	2.97	3.20	2.66	3.11	5.56	1.83		
F (vacil)	2.51	2.97	3.20	2.66	2.98	3.05	2.41		
N_{max} (sone)	7.77	11.83	10.34	11.68	9.86	15.54	2.46		
N_M (sone)	3.81	4.63	3.91	4.34	3.70	4.07	2.20		
N_σ (sone)	1.46	2.60	1.85	2.20	1.69	3.00	0.10		
N_5 (sone)	6.72	10.12	6.91	8.42	6.79	7.15	2.52		
S_{ZwM} (acum)	1.09	1.08	1.08	1.07	1.10	1.10	1.47		
S_{Aumax} (acum)	2.06	3.20	2.70	3.02	1.99	2.25	2.09		

The jury test was conducted as follows:

1) A S.A.O. of 60 people in the 18-30 year-old range was chosen. The S.A.O. hearing ability was previously verified by an audiometric analysis.

2) A Semantic Differential method was applied to the S.A.O. for the preliminary analysis; this method was preferred for the preliminary analysis as opposed to Pair Comparison method because observers may lose concentration on the test if subjected to too many comparisons. Results obtained by Semantic Differential method were used to sort the investigated signals in terms of annoyance or pleasantness. S.A.O was subjected to three different random sessions constituted by the investigated signals. In this way, S.A.O. is not influenced by the order of presentation of the signals. The following parameters were chosen to be found by the S.A.O.

- annoying/not annoying to characterize the noise inside the vehicle cabin;
- unpleasant/pleasant to characterize the vehicle solidity and stability; a noise signal may give the passenger a sense of sturdiness. This fact is represented by a pleasant sensation.

Jury test parameter values are in [1, 7] range for Semantic Differential method. Maximum value corresponds to a highly good signal while minimum value corresponds to a highly bad signal. Thus, parameter scale values are associated to different descriptors. Average results of the three sessions are reported in Table 2 for each parameter (“No annoyance” and “Pleasantness”).

Table 2. Semantic Differential jury test results

Squeaking noise (Reference Number)	*No annoyance*	*Pleasantness*	*Squeaking noise (Reference Number)*	*No annoyance*	*Pleasantness*
1	4.26	5.01	14	4.09	3.58
2	3.86	4.11	15	2.53	3.29
3	3.34	3.57	16	2.83	3.15
4	4.21	4.52	17	3.92	3.88
5	4.10	4.00	18	3.28	3.64
6	3.47	3.95	19	4.36	4.29
7	3.41	3.66	20	3.02	3.34
8	3.22	3.10	21	3.62	3.86
9	3.67	3.91	22	3.45	3.55
10	2.78	3.03	23	4.55	3.75
11	5.36	4.45	24	3.92	3.38
12	2.71	3.00	25	6.28	5.19
13	5.66	4.69			

3) A Pair Comparison method was applied to signals characterized by similar characteristics in terms of annoyance and pleasantness. The eight worst noises obtained by the Semantic Differential method were chosen for each subjective parameter. Thus, the signals for Pair Comparison analysis are selected close to each other in terms of the evaluation given by the Semantic Differential Method and they are probably similar in terms of disturbance given to the car passenger. In this way, relations obtained by regressive analysis are very accurate. It was shown that generally the same squeaking noise is disturbing for both the annoyance and pleasantness scale (an annoying squeaking noise gives a sense of vehicle fragility). The S.A.O. was asked "which noise is less annoying" and "which noise is more pleasant". Jury test parameter values are in the [0, 1] range, where 0 corresponds to a signal which was never chosen by the S.A.O. and 1 to a signal which was always chosen by the S.A.O. Thus, small values are associated to negative characteristics, in a way close to the Semantic Differential scales. Average results obtained by the Pair Comparison jury tests are shown in Table 3 for each parameter.

Table 3. Pair Comparison results and Comparison with values given by the proposed relations

No Annoyance				*Pleasantness*			
Squeaking Noise Ref. Number	*Pair Comparison Jury test*	*Eq. (1) values*	*Δ*	*Squeaking Noise Ref. Number*	*Pair Comparison Jury test*	*Eq. (2) values*	*Δ*
3	0.68	0.71	-0.03	8	0.48	0.45	0.03
8	0.62	0.60	0.02	10	0.30	0.32	-0.02
10	0.38	0.35	0.03	12	0.24	0.23	0.01
12	0.44	0.45	-0.01	15	0.44	0.41	0.03
15	0.29	0.28	0.01	16	0.38	0.40	-0.02
16	0.50	0.47	0.03	20	0.51	0.52	-0.01
18	0.59	0.57	0.02	22	0.49	0.47	0.02
20	0.43	0.43	0.00	24	0.50	0.48	0.02

4) A regressive analysis was performed in order to find relations between the selected subjective parameters ("No annoyance" and "Pleasantness") and the objective psychoacoustics metrics. Analysis was carried out for the signals subjected to the Pair Comparison method.

The following optimum relations were obtained for the parameters "No annoyance" and "Pleasantness" (see also Table 3):

$$\mathrm{NoAn_s} = -0.32 \cdot \mathrm{N_M} - 0.41 \cdot \mathrm{S_{Au\,max}} + 3.22 \quad (1)$$

$$\mathrm{Pl_s} = -0.10 \cdot \mathrm{N_{max}} - 0.30 \cdot \mathrm{N_M} + 0.39 \cdot \mathrm{N_\sigma} + 2.08 \quad (2)$$

Equations (1, 2) show that both "No annoyance" and "Pleasantness" increase when loudness and sharpness mean or maximum values decrease. Besides, a squeaking signal characterized by a wide range of loudness values (high N_σ values) may give a sense of compactness to the passenger. The proposed relations (1, 2) were validated by applying them to the signals investigated with the Semantic Differential method. The order of preference given by the S.A.O. (Semantic Differential jury test) and the one obtained by the proposed relations were compared. Results show that:

- the average difference between the orders of preference is 1.24 places and standard deviation is 1.65 for parameter "No annoyance"; Spearman's rank correlation coefficient is 0.980 [6].
- the average difference between the orders of preference is 1.20 places and standard deviation is 1.66 for parameter "Pleasantness"; Spearman's rank correlation coefficient is 0.975 [6].

A quantitative description of psychoacoustic annoyance due to synthetic and technical sounds (such as car noise, air conditioner noise, sawing noise, drilling noise) may be obtained also by the following well-known model proposed by Widmann [4]:

$$\mathrm{PA} = \mathrm{N_5}\left(1 + \sqrt{w_S^2 + w_{FR}^2}\right) \quad (3)$$

where

$$w_S = (\mathrm{S_{ZwM}} - 1.75) \cdot 0.25 \cdot \log(\mathrm{N_5} + 10) \qquad \text{for } \mathrm{S_{ZwM}} > 1.75 \quad (4)$$

$$w_{FR} = \frac{2.18}{(\mathrm{N_5})^{0.4}} \cdot (0.4 \cdot \mathrm{F} + 0.6 \cdot \mathrm{R}) \quad (5)$$

Each analysed squeaking signal is characterized by $S_{ZwM} < 1.75$. Thus, the model given by relation (3) was applied with $w_S = 0$. The comparison between the order of preference given by the S.A.O. (Semantic Differential jury test) and the one obtained by eq. (3) model gives a Spearman's rank correlation coefficient equal to 0.944. The correlation coefficient is less than the one obtained by the proposed relation (1). This is due to the fact that the investigated squeaking noises are characterized by low sharpness values. Thus, the proposed model gives a better annoyance evaluation compared to eq. (3) for low sharpness noise signals.

4. CONCLUSIONS

Squeaking noises produced inside a vehicle cabin were analysed by objective and subjective measurement campaigns. Psychoacoustic metrics such as loudness, sharpness, roughness and fluctuation strength were measured. A jury test was applied to a S.A.O. by Semantic Differential and Pair Comparison jury tests. Relations for annoyance and pleasantness evaluation were proposed by Pair Comparison results: they shows that:

- annoyance due to a squeaking noise increases with the loudness mean and the sharpness maximum value;

- pleasantness due to a squeaking noise decreases when the loudness mean and the loudness maximum value increase; it increases with the loudness standard deviation;

The proposed indexes were validated by comparing the order of preference given by the regressive relations with the results obtained by Semantic Differential jury tests. Results show that the Spearman's rank correlation coefficient is:

- 0.980 for "No annoyance" parameter;
- 0.975 for "Pleasantness" parameter.

Besides, the proposed models for psychoacoustic annoyance were compared to a well-known model relative to synthetic and technical sounds. The comparison showed that the proposed models are more correlated to the S.A.O. results than the bibliographic model relatively to the investigated signals (squeaking noises inside vehicle cabins) because this kind of signals is characterized by low sharpness values. Thus, the proposed relations may be used to evaluate with high accuracy the squeaking noise impact upon car passengers by using loudness and sharpness metrics. Motor vehicle factory designers may use the proposed relations in order to design a comfortable motor vehicle.

5. SYMBOLS

Symbol	*Description*	*Units*
Δ	Estimation Error	
F	Fluctuation Strength	vacil
N_M	Statistical loudness mean	sone
N_{max}	Statistical loudness maximum value	sone
$NoAn_s$	"No annoyance"	-
N_σ	Statistical loudness standard deviation	sone
N_5	5 percentile statistical loudness	sone
PA	Psychoacoustic annoyance defined by Eq. (3)	-
Pl_s	"Pleasantness"	-
R	Roughness	asper
S_{Aumax}	Aures statistical sharpness maximum value	acum
S_{ZwM}	Zwicker statistical sharpness mean	acum

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