

Effect of temperature variation on the perceived annoyance of rattle sounds in the automotive industry

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ABSTRACT

Product quality improvements and electrification in automotive industries, denote the growing need for squeak and rattle free cars. Studying the relation between main sources of rattle sound, like temperature changes and the emitted sound can help to improve the design robustness. In this research, the effect of temperature on the perceived annoyance level of rattle sounds that are generated from selected material pairs from the car cabin is studied. The sound stimuli were collected from a rattle test apparatus by binaural technology in laboratory condition, by a parameter study on temperature, gap and material pairs. Estimated annoyance levels, using the psychoacoustic metric developed through a subjective listening survey, show that perceived annoyance of rattle sounds varies differently for various materials in different ambient and boundary conditions. Employing this approach can lead to a rattle sound database for material pairs to be incorporated with geometry variation results for requirement setting and design robustness improvements in the early development phases of passenger cars before the physical prototypes are available.

Keywords: Squeak and rattle, Subjective listening test, Temperature variation, Psychoacoustic metrics

1. INTRODUCTION

In the view of customers, the presence of squeak and rattle implies a defect in the car and the need for a workshop visit, which incur additional warranty costs to carmakers (1). The rattle is a phenomenon that happens when two adjacent parts impact and make nonstationary impulsive noises. This can happen in a car cabin due to various reasons. An improper design concept, an inappropriate set of materials, ageing and change in ambient condition can cause a silent car to start demonstrating squeak and rattle problems. Yet, the effect of many of these contributors are not fully taken into account during design phases and they are mainly dealt with only when physical prototypes and especially physical complete vehicle prototypes are available (2). The main reason for this is either the lack of knowledge about highly nonlinear mechanisms behind squeak and rattle, or the lack of proper methods capable of predicting squeak and rattle status in design phases. Therefore, understanding the contribution of important parameters to the generation of squeak and rattle sounds, like the ambient condition variation, is a key step towards the upfront prediction and elimination of squeak and rattle events in car design and development processes. Temperature change not only is a source of occurrence of rattle sounds but it can have an impact on the quality of the generated sound as well. This is both due to the resulted geometrical variation imposed by expansion or shrinkage of parts, as well as the change in mechanical properties of impacting parts (3). Squeak and rattle have been studied under temperature changes. Trapp and Pierzecki studied the effect of temperature change (+20 °C and +49.8 °C) on the sound pressure level of generated squeak sound for selected coatings for automotive elastomers and plastics (4). However, previous studies (5) showed that in order to capture the behaviour of rattle sounds psychoacoustic parameters, like Zwicker loudness (6), have to be employed. There have also been studies to improve the prediction of the perceived annoyance of rattle sounds by considering the impulsive behaviour of rattle sounds (7) and utilising other psychoacoustic parameters than loudness (8). Thus, the previous studies suggest the importance of conducting research on the effect of temperature change on generated rattle sounds from different materials, incorporating psychoacoustic parameters.

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In this study, it is shown that the temperature variation during the generation of rattle sounds influence the perceived annoyance of rattle sounds to different extents for different plastic and metallic materials. The conclusions are made with the aid of a psychoacoustic metric that was designed based on the listening jury survey that was conducted in this work. In order to study the temperature effect in a broader operational range, a rattle generating apparatus was built that facilitates parameter variation, like different impact gaps and material pairs, in the design of experiments.

2. DESIGN OF EXPERIMENTS

2.1 Parameter Variation

Plastic and metallic parts have different physical properties, and they can be influenced by temperature changes to various extents. In this research, the materials that were studied include steel (St), aluminium (Alu), Polypropylene (PP), PC-ABS (PC) and Polyamide 66 (PA66). These materials are widely used in interior trim parts of passenger cars as well as in the structural components of the instrument panel and side doors. Rattle sounds were generated in different temperatures: +40 °C (10% relative humidity); +20 °C (50% relative humidity); -10 °C (40% relative humidity). In order to generate the rattle sounds under controlled laboratory condition, a test stand was designed and built that is depicted in Figure 1. The test stand consisted of an aluminium beam (1) with a rectangular cross section, which was clamped at one end and on the tip of the beam at the other end an exchangeable material insert was included (2). The beam was excited by a quiet shaker (3) that was attached to the beam by a rod (4). The material insert at the end of the beam was located in front of an exchangeable counterpart with the same geometry as the insert. The counterpart was attached to an impact hammer (5) that was fixed to the test stand through a length adjusting mechanism (6). The adjustable length was used to vary the contact gap in the impact point at the tip of the beam with a precision of 0.1 mm. The experiments were done by adjusting the installation gap between the two material inserts from a minus gap (pretention condition) to the zero gap (just in touch condition) and positive gaps. The design space for different material pairs and variations of gap and temperature are summarised in Table 1. The experiments were performed for a full one-sided pair test and the results were measured for all gap and temperature variations for each material pair.

Table 1 - Parameter variation in experiments

Parameter	Parameter variation				
Material samples	Steel	Aluminium	PP	PC-ABS	PA66
Initial Gap at impact point (mm)		+1	+0.5	0	-0.5
Temperature (°C) @ humidity	+40 @ 10%		+20 @ 50%		-10 @ 40%

For the apparatus to comply with the behaviour of the interior parts of the passenger cars, the first eigenvalue of the beam was adjusted to happen at 40 Hz. This lies between the common range for the first eigenvalue of body, closures and interior subsystems of a passenger car (35 to 45 Hz). For further information about the design details of the test setup please refer to (9).

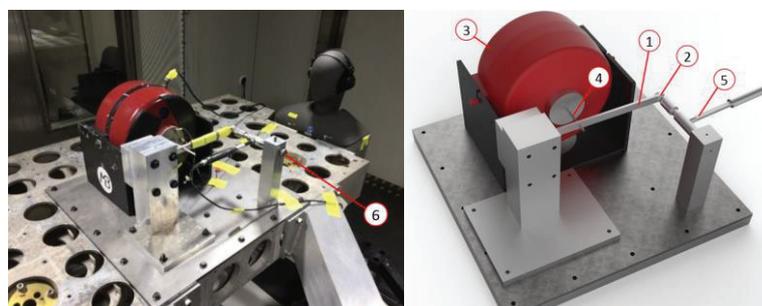


Figure 1 - Rattle producing apparatus used to collect sound samples

2.2 Data Acquisition

A stochastic signal was defined as the input signal in a way to reach the recommended value of 0.5g

acceleration at the impact point in a frequency range of 20 to 100 Hz (1). Audible squeak and rattle sounds are in the frequency range of 200-10000 Hz (2). During the test, at frequencies above 200 Hz, the background noise level was measured below 20 dB, which is in the recommended range for performing squeak and rattle tests (1). For a better reproduction of the recorded sound stimuli in the listening test, the sound collection was performed by using BHS II binaural headset mounted on an HMS IV artificial head connected to SQuadriga II data acquisition system, all from Head Acoustics. The acoustic head was located at 60-cm-distance in front of the impact point and at the same height. The complete test setup is shown in Figure 1, where the test stand is mounted in the semi-anechoic climatic chamber. Sound recording was done at the sampling rate of 48 kHz and with 24-bit quantisation. The sound samples were trimmed into five-second-long sound signals with the peak nonstationary loudness of the recorded sound happening at the centre of each stimulus.

3. LISTENING JURY TEST

In this work, in order to elicit the opinions of people about the annoyance level of rattle sounds, a subjective listening test was done. The design and conduction of the experiment were done by following the guidelines for conducting listening clinics (10), to guarantee the objectivity, reliability and validity of the experiment. The listening test was set in a listening room with the calibrated headphones and the projected in-cabin image of a passenger car. The experiment was a paired comparison with magnitude estimation (10) and the participants were asked to listen to pairs of sounds at each time and decide on the relative annoyance level of the second stimulus, assuming the annoyance level of 100 for the first sound. The length of each sound stimulus was trimmed to five seconds, followed by one second of silence and then the next five-second stimulus. Three stimuli were selected as the reference sounds among the pairs: the recorded sounds in room temperature from the steel/steel, PC-ABS/PC-ABS and PC-ABS/aluminium pairs with +0.5 mm gap at the impact point. These three sounds were used to facilitate the judgement task by comparing different combinations of metallic or plastic materials against a reference sound from the same category. However, in order to reduce the probable biasing effect, some of the stimuli were rated against a reference sound from a different category. The full-block paired comparison of the reference pairs was included in the experiment. The experiment consisted of 105 pairs, played back in a randomised order, out of which 21 pairs were allocated for response consistency check. This resulted in a 28-minute-long experiment, excluding the introduction session before each trial and feedback session at the end. In total, 18 jurors participated in the experiment. All were using cars at least on a weekly basis, among which 8 were expert engineers dealing with squeak and rattle sounds in the automotive industry. The average age of the participants was 36.4 years. The demographics of the participants are presented in Figure 2. Participants were 13 males and 5 females and all had a normal hearing ability. Majority of the participants did not have high knowledge of psychoacoustics and experience in listening tests. Apart from the expert engineers, the rest had low experience on the measurement of squeak and rattle sounds.

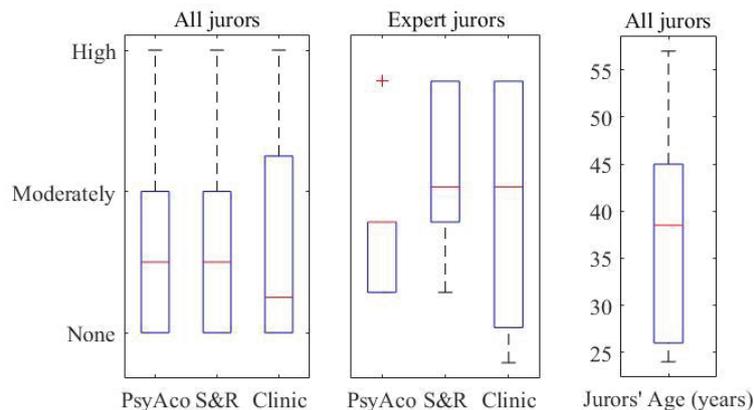


Figure 2 - Listening clinic jurors' information. PsyAco: psychoacoustics knowledge; S&R: experts in S&R; Clinic: previous experience in listening test

4. RESULTS OF THE LISTENING JURY TEST

The consistency of each participant was calculated using the results of the circular triads and

repeated pairs in the paired comparison experiment. The responses of the jurors with consistency value above 50% were opted to be used in this study, resulting in excluding the responses from two of the participants. In addition, among the pairs, there were some sound stimuli that did not receive consistent responses from most of the jurors, mainly because of the relatively lower sound pressure levels compared to the reference stimuli. This included five room temperature stimuli and two cold condition stimuli that were excluded from the study. Mean values of the measured rattle relative annoyance for all participants and expert jurors for three material pairs are given in Figure 3. The boxplots in Figure 3 show the first and third quartile values and the responses beyond the distance equal to the interquartile distance from the box edges are considered as outliers. The arithmetic average and median of responses are presented by stars and dash lines, respectively. Apart from the just in touch condition (0 mm gap) for Aluminium-Aluminium pair in all temperatures and for Steel/PP in room temperature and for PP-PA66 in cold temperature, the difference between mean values of all participants and expert jurors were below 10%. Adjusting the gap for the just in touch condition was very sensitive to the mechanical adjuster in the apparatus, resulting in less reliable responses from the subjective listening test. This is also reflected in the large confidence intervals of results for the sounds recorded in the just in touch condition, as shown in Figure 3.

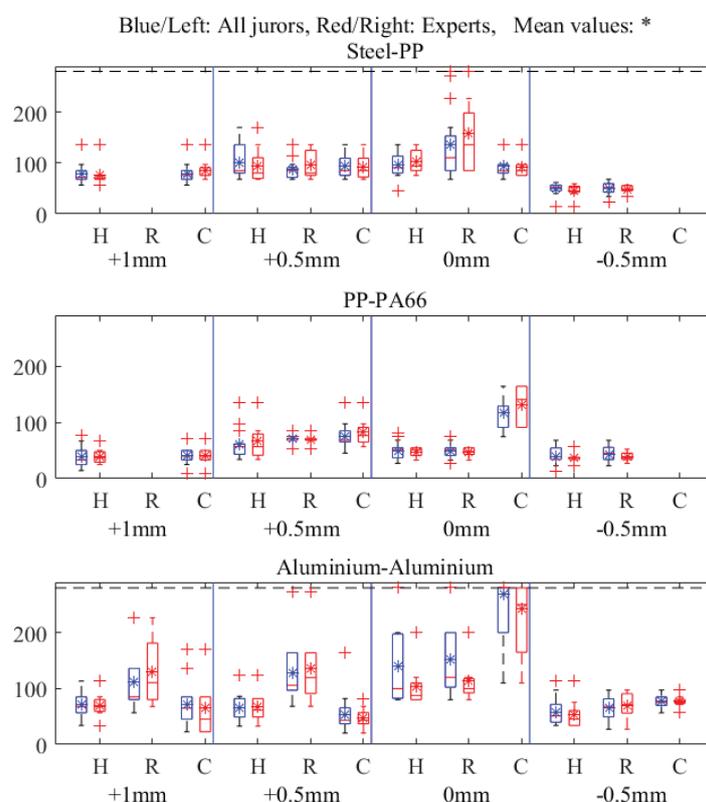


Figure 3 - Subjective rattle relative annoyance for temperature variation; H: hot (+40 °C), R: room temperature (+20 °C), C: cold (-10 °C))

5. PSYCHOACOUSTIC CHARACTERISATION

In this study, in order to provide a more quantified and objective understanding of the effect of temperature variation on the annoyance level of rattle sounds for material pairs in the car cabin, psychoacoustic metrics were used. Firstly, the best-correlated metrics with listening jury test were identified and then the estimated annoyance levels of all recorded sound stimuli were calculated.

5.1 Psychoacoustic Parameters

Rattle sounds have fast time-varying properties and often a rattle sound is composed of very short events. Henceforth, to capture the overall characteristics of the rattle sounds different standard psychoacoustic parameters need to be incorporated (5,7,8,11). Accordingly, in this work, the following single value parameters were employed to predict the perceived annoyance of rattle sounds.

5.1.1 Nonstationary Loudness DIN 45631/A1 (N)

Loudness is a fundamental psychoacoustic measure that represents the human perception of sound volume with a linear scale. The unit of loudness is sone. The loudness of 1 sone by definition corresponds to a sine tone of 1 kHz frequency with a sound pressure level of 40 dB (6). In DIN 45631/A1, calculation method was extended to determine the loudness of time-varying sounds.

5.1.2 Sharpness DIN45692 (S)

Sharpness determines the ratio of the high-frequency content of a sound signal. Sounds with high sharpness cause higher irritation as perceived by humans. Sharpness is measured by acum. One acum corresponds to the sharpness of a narrow band noise at 1 kHz and a sound pressure level of 60 dB (6).

5.1.3 Roughness (R)

Roughness represents the human perception of variation in the frequency content of a sound that often happens as pulsation or beating. Roughness is measured by aspar. One aspar equals to roughness of a tone sound at 1 kHz and 60 dB sound pressure level that its amplitude is 100% modulated at a frequency of 70 Hz. The calculation is based on the hearing model of Sottek (12).

5.1.4 Impulsiveness (I)

Impulsiveness indicates how humans perceive the distinctive sound level alterations that happen in fast events. It indicates how fast and intensive sound signal changes with respect to the stationary background noise. The calculation method is based on Sottek hearing model and can be found in (13).

5.1.5 Kurtosis (K)

Kurtosis is a statistical measure that can indicate the presence of peaks in a signal. Therefore, it can be an indication of impulses in a sound signal. Compared to impulsiveness, Kurtosis is not a psychoacoustic measure and does not have a linear relation with human feeling (13).

5.2 Psychoacoustic Annoyance Metric (PA)

Subjective results of the listening jury test were used as the ground to identify the psychoacoustic metrics that capture the annoyance level of the recorded rattle sounds with the highest precision. Referring to the results of the jury test, partly presented in Figure 3, the mean values lies within the interquartile range and close to the median, for almost all of the sound stimuli apart from just in touch condition. In addition, the difference between mean value results from expert and non-expert jurors, for most of the sound stimuli apart from the just in touch condition, was less than 10%. Hence, arithmetic mean value results of all participants were chosen for identifying the psychoacoustic parameters that best capture the annoyance level of rattle sounds. Stimuli that received responses with the highest consistency, less skewed responses and the least standard deviation values from the results of the listening test were chosen for designing the rattle annoyance metric as presented in Table 2.

Table 2 - Selected pairs for psychoacoustic metric design

Gap variation	+1 mm	+0.5 mm	0 mm	-0.5 mm
Steel-PP	H - C	- R -	-- C	HR -
PP-PA66	-- C	- R -	HR -	HR -
Alu-Alu	H --	H - C		HRC

H (Hot): +40 °C, R (Room temperature): +20 °C, C (Cold): -10 °C.

For each stimulus, the arithmetic mean, maximum value and 95th and 90th percentile values of the psychoacoustic metrics, introduced in section 5.1, were calculated and normalised using Artemis SUITE 8.2 software and MATLAB. The coefficient of determination (R^2) and root-mean-squared error (RMSE) values for the normalised psychoacoustic measures versus normalised jury results of the selected pairs, indicated in Table 2, were calculated. Based on the calculated correlation and error values the following measures were identified to best describe the annoyance level and to be used in the regression solution for the psychoacoustic annoyance metric:

- I_{10} : 90th percentile value of impulsiveness
- K_m : the arithmetic average of Kurtosis measure
- N_{10} : 90th percentile value of nonstationary loudness
- S_{10} : 90th percentile value of sharpness
- R_5 : 95th percentile value of roughness

The above measures were employed in nonlinear multivariable regression with constrained coefficients to design the rattle perceived annoyance metric. After examining multiple regression solutions, terms with low significance and effect on the response were removed from the regression solution. The best fit was achieved with the coefficient of determination values (R^2) of 0.46 and 0.60 and root-mean-squared error ($RMSE$) of 32.17 and 10.60 for all sound stimuli and the selected stimuli (in Table 2), respectively. The psychoacoustic annoyance metric (PA) is given in Equation (1)

$$PA = 0.53I_{10} + 4.55K_m + 0.63N_{10} + 1.54R_5 + 0.01K_m^2 + 0.99R_5^2 - \frac{9.97}{I_{10}} - \frac{0.36}{N_{10}} - \frac{13.7}{S_{10}} + 55.01 \quad (1)$$

6. RESULTS OF PSYCHOACOUSTIC ANNOYANCE METRIC AND DISCUSSION

The calculated annoyance values by proposed psychoacoustic metric (PA) in Equation (1), in comparison to the measured annoyance levels from the listening test for temperature variation, are given in Figure 4. For the cases with the absence of an interval box, no experimental results were available. The sound stimuli that were used in the regression solution in Equation (1), are marked by blue diamonds on the x-axis in Figure 4. Alongside the estimated values by PA , the psychoacoustic single values present in the PA formulation are illustrated in Figure 4. In most of the cases, apart from the zero-mm gap, the PA metric estimates the trend of the change in perceived annoyance levels for varied temperatures and within the interquartile range of the measured results. In agreement to a previous study (5), Results also confirm that among the individual single values, nonstationary loudness best estimates the annoyance levels of the sound stimuli. However, the proposed PA metric is capable of predicting the trend of changes in the perceived annoyance levels with higher accuracy.

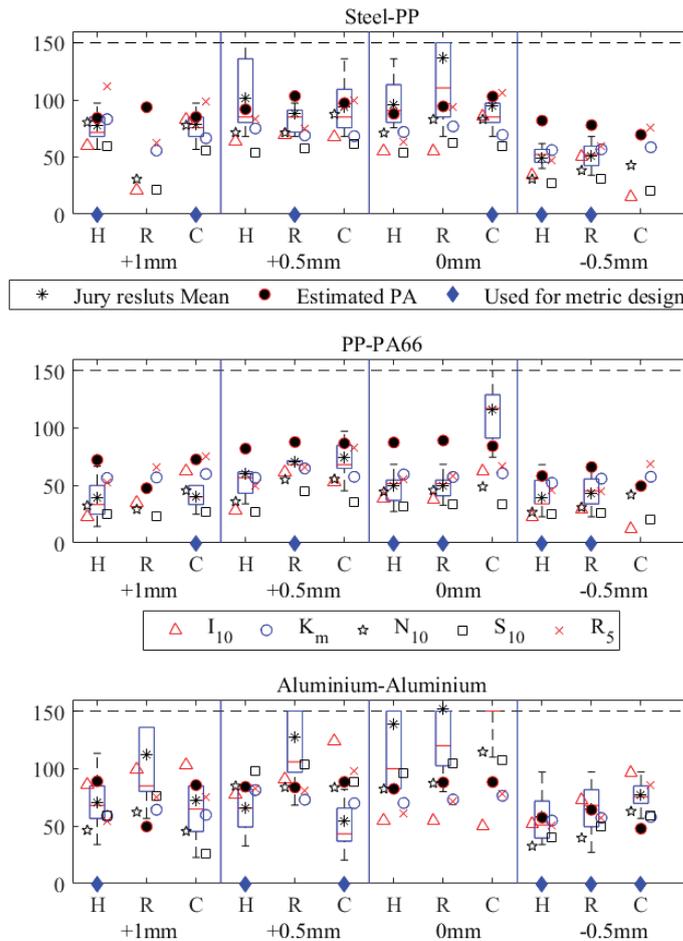


Figure 4 - Estimated PA and normalised single psychoacoustic values vs. measured rattle annoyance for temperature variation; H: hot (+40 °C); R: room temperature (+20 °C); C: cold (-10 °C)

Using the proposed annoyance metric (*PA*), annoyance levels were calculated for all recorded sounds from all material pairs in all impact gap and temperature conditions, as listed in Table 1. The estimated annoyance levels by *PA* metric for hot and cold temperature results relative to room temperature are depicted in Figure 5. For a better understanding, the results are clustered for different material pairs of types metallic-metallic, metallic-plastic and plastic-plastic pairs. Referring to the results given in Figure 5, for metallic pairs, in 50% of the cases a decrease in temperature results in 12.7% higher perceived annoyance on average. In 8% of cases, a decrease in temperature reduces the annoyance level by 10.2%, on average. In the remaining 42% of cases, a clear trend is not observed. For plastic pairs, 33% of the cases indicate an average increase of 8.7% in the annoyance level by a decrease in the temperature, while just 4% of the results show an adverse effect with an average of 4.8% and in 63% of the cases a clear observation cannot be recognised. For cross material combinations of metallic-plastic pairs, in 46% of cases, a drop in temperature leads to sounds with 9.7% higher annoyance level, on average and the other 54% of results do not denote a clear pattern. Parts with just in touch (0 mm gap) and small positive gap conditions are the common sources for the generation of rattle sounds in the car cabin. If only gap conditions of +0.5 mm and 0 mm are taken into account, in 69% of the cases, a drop in temperature makes the generated sounds to be perceived 8.5% more annoying on average. However, 24% of the results show an opposite effect with an average of 8.5% less perceived annoyance.

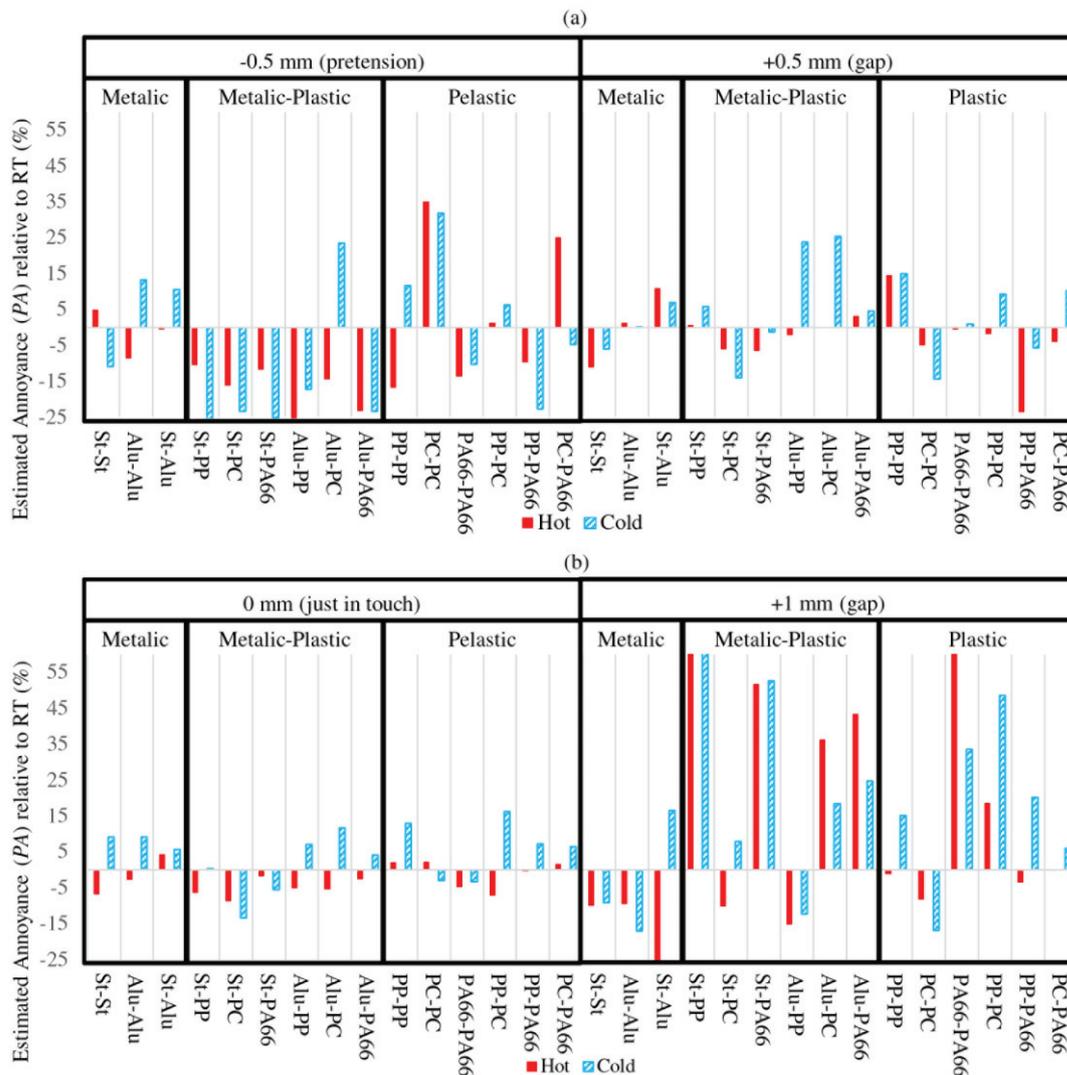


Figure 5 - Estimated annoyance by *PA* metric relative to room temperature for clustered material pairs. (a) -0.5 mm and +0.5 mm gaps; (b) 0 mm and +1 mm gaps;

7. CONCLUSIONS

In this research, the effect of temperature variation on the annoyance level of rattle sounds generated in the laboratory condition was investigated. It was shown that temperature variation has a significant effect on the perceived annoyance of generated rattle sounds that can result up to 40% change in perceived annoyance level, for a change of temperature from -10 °C to +40 °C. It was discussed that according to the results of estimated annoyance levels for all different material pairs of types metallic-metallic, plastic-plastic and metallic-plastic, the risk of generation of rattle sounds with higher annoyance levels is more probable to increase by a temperature drop. However, in some cases, an adverse effect was observed. The annoyance metric proposed in this work was designed by the nonlinear multivariable regression solution with constrained coefficients with reference to the results of the conducted listening test. The method for measuring the perceived annoyance level of the rattle sounds in the experiment was paired comparison with magnitude estimation. The sound stimuli were recorded from a rattle producing apparatus that was built for this work. The single values of the standard psychoacoustic parameters were employed in the formulation of the proposed psychoacoustic metric. The approach used in this study, to estimate the annoyance level of emitted rattle sounds in the car cabin as a result of temperature variation, can be employed to develop a rattle test machine that can be used to form a database for different automotive material pairs at different boundary conditions when exposed to various ambient conditions. This database can be incorporated with geometry variation analysis results to increase the robustness in the design development phases of a passenger car. By knowing the impact of temperature change on resultant rattle sounds, requirements for gap and pretension in critical interfaces can be adjusted accordingly during the requirement setting phases. In addition, this database can be employed to help the treatment and understanding of rattle issues in the physical verification phase and the end-of-line activities in the production phase as well.

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