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Technical note

Psychoacoustic analysis of power windows sounds: Correlation between subjective and objective evaluations

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ABSTRACT

The sound quality of automotive components is becoming more and more important in the customer perception of the vehicle quality. In the present study, the sound quality of power windows was investigated through subjective and objective analyses of experimentally recorded sounds. In particular, a jury test based on Verbal Attribute Magnitude Estimation and Paired Comparison techniques was developed and presented. The combination of the two methods is a novel aspect with respect to the literature and resulted in a useful and simpler mean to obtain coherent subjective judgments. In order to quantify the power window sound quality, objective parameters were obtained applying acoustic and psychoacoustic metrics, resulting well correlated with the correspondent subjective evaluations. Additionally, correlation analyses between subjective overall (i.e. independent) judgements on sound quality and subjective dependent or objective parameters were performed. Regression analyses were applied to develop models of perceived component quality, powerfulness and annoyance. The subjective and objective quantities related to the features of loudness, sharpness and steadiness of the electric motor were found to be prominent in sound quality evaluation.

1. Introduction

The customer perception of the overall quality of a car is made up of many different factors, among which sound quality is becoming more and more crucial. Thus, in the last decades, increasing attention has been paid to the development and application of acoustics and psychoacoustics approaches in order to predict customers' expectations and satisfaction of the sound quality of automotive components, e.g. [1]. Although it can appear a minor aspect in the perception of the quality of a car, the sound produced by the power window regulator is also gaining special attention, particularly for high-end cars, as witnessed by the rather numerous studies in this field. This can be explained observing that power windows are frequently actuated by the customers within a car showroom [2], i.e. in a rather silent environment, and therefore represent one of the first 'interactions' with the vehicle.

The literature on power window sound quality deals with many aspects, spanning from the definition of the experimental set-up for measuring car interior noise [3] to the identification of noise mechanical sources and design guidelines [4], from the temporal and frequency features of the power window acoustic signals [4] to the techniques for objective measurements and subjective evaluations of the noise emitted by automotive components [2]. In particular, objective noise characterization has been faced with different approaches: psychoacoustic metrics [2,5], order analysis for the relative RPM deviation (e.g. motor DIP [2,6]), artificial neural networks and fuzzy logic [7], and Finite Element analyses [4,8]. Additionally, many different time-frequency analysis techniques have been applied: fast and short time Fourier transforms, spectrograms, power spectral density [9,4,6], Wigner-Ville distribution and ambiguity function, and wavelet transforms [10]. It is worth noting that time-frequency analyses and psychoacoustic metrics are usually considered the most appropriate approaches for objective sound characterization and are often used also for defining threshold values. On the other hand, subjective noise evaluation has been based mainly on listening jury tests, e.g. individual preferences rating scales and paired comparison tests [11,12,2,3].

The possibility of predicting the overall sound quality of a product is considered extremely valuable by automotive component manufacturers. For this purpose, objective characterizations and subjective evaluations, e.g. psychoacoustic metrics and jury tests, are usually correlated. Such a correlation typically involves the application of statistical concepts (e.g. "pair-wise T-test" confidence intervals, Pearson's correlation coefficient, linear/non-linear single/multiple regression and determination coefficient) and techniques (e.g. factor analysis, principal component analysis, variance analysis and scatter plot) [9,12,13,3].

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The present study is focused on the assessment of the sound quality of power windows regulators by means of an '*ad hoc*' procedure, correlating subjective and objective evaluations. As a case study, four different power windows were considered, from different types of vehicles in terms of class and age. The perceived sound quality was evaluated by means of a listening jury test purposely developed and administered to a statistically significant sample of subjects. With respect to the literature the present study is based on a much larger sample, i.e. 90 subjects vs. 27 in [12] and 35 in [2]. Moreover, the paired comparison test (PCT) [13] was used in combination with the verbal attribute magnitude estimation (VAME) approach to assess the sound quality of power windows. In most studies, only one type of jury test is used, e.g. the VAME in [2,14,7] and the PCT in [15]. Alongside, an objective noise characterization was performed by computing and analysing standard acoustic metrics. The results obtained from the two analyses were combined in order to evaluate possible correlations between subjective and objective variables, and hence to develop psychoacoustic models useful for both sound quality prediction and design optimization of power windows.

2. Methods

In this section the main elements of the activity are described, starting from the details of the sound recording procedure. Then, the concepts employed for the objective sound quality assessment and psychoacoustic analysis are introduced and commented. The subjective evaluation procedure is also reported, with a description of the development and processing of a listening test questionnaire. Finally the correlation analysis performed between subjective and objective evaluations is described.

2.1. Sound recording, processing and reproduction

2.1.1. Recording

The experimental activity of sound recording was carried out in a parking area close to the Department building, during quiet hours. Four different vehicles were selected in order to have rather marked differences in the power window sounds, as observed in [16]: two economy cars and two mid-size cars. One of the latter was new whilst the others were 4–6 years old. The reason for having restricted the analysis to four cars is to limit the time required for questionnaire filling in order to not lose the subject's concentration, as generally suggested.

The sound acquisition system included binaural microphone headphones and software and hardware ARTeMIS® Squadriga connected to a laptop. The binaural headphones have an internal reference for calibration when used with the full scale of 94 dB, allowing capturing the sound spaciousness.

For each car, a sequence of 5 opening-closure cycles (O-C cycle, with O = opening and C = closure), with a 3 s pause between each motion inversion, was acquired. The headphones were worn by a subject sitting on the driver's seat and thus close to the sound source. The recording was performed by means of real time visualization of the audio tracks that enabled to identify and discard the tracks corrupted by transient events, such as passing vehicles or machinery operations nearby. As an example, Fig. 1 shows, for a given recorded track, the *Sound pressure level* (*SPL*) during 5 O-C cycles, for both the left and right headphone channels (Fig. 1(a)), and the spectrogram of the first O-C cycle (Fig. 1(b)). The temporal trend of the *SPL* during a single cycle clearly shows the sequence of the O and C phases, each one characterized by an initial and a final transient segment (related to the window-seal interaction), separated by a central quasi-steady phase. Additionally, the spectrogram points out that the opening phase is shorter than the closure one. The comparison of the *SPL* during the opening and closure phases also highlights the difference in the background noise with closed/open window (Fig. 1(a)). The capability to evaluate the background noise in real time provided useful indications for the choice of the quietest area available in the parking lotto, in order to avoid eventual saturation problems due to sound pressure peaks.

2.1.2. Sound processing

The sound tracks, stored in *wav* and *ascii* files, were then post-processed in Matlab®. For each sound track, a single O-C cycle was selected, choosing the one with the best record at the left channel, which is the closest to the sound source. Such a selected cycle, referred to as "sound" throughout the manuscript, was used for both objective and subjective evaluations. In particular, data processing for the evaluation of objective sound quality assessment is detailed in Section 2.2.

It should be noted that objective characterisations were performed considering different segments of each sound sample:

I. Stationary segment of the window opening phase (*SO*);
II. Stationary segment of the window closing phase (*SC*);
III. Total O-C cycle, including both transient and stationary segments (*TOC*);
IV. Filtered total O-C cycle, obtained using a Butterworth low pass filter of the 4th order with a cut-off frequency of 1.5 kHz (*FTOC*).

On the other side, for subjective evaluations, the complete O-C cycle was included in the questionnaire because considered more representative of the actual sound.

2.2. Objective sound quality evaluation

Objective sound quality assessment consisted in time-frequency analysis and psychoacoustic analysis, according to methods well assessed in the literature. The microphone signals were thus processed using some general analysis tools, available or purposely implemented in Matlab® and Labview®. The following objective variables were evaluated, from time-frequency analyses:

- *Sound pressure level* (*SPL*) vs. time with "Fast" time exponential averaging, with reference value p_0 = 20 μPa. It was expressed in dBA applying A-weighting to account for the different sensitivity of the human ear in the frequency range. In addition to the temporal trend, the peak value (SPL_p), the mean value (SPL_m) and the root mean square value (SPL_{rms}) of the *SPL* functions were evaluated.
- *Kurtosis* (*K*) of the instantaneous sound pressure signal, computed according to [4]. This quantity was analysed because it is considered related to the squeak phenomenon observed mainly at the start-up of the electric motor, that is at the glass detachment from the seals, but also present in other phases of the glass motion. In particular, according to [4], for the stationary phase of the power window motion, values of $K > 15$ denote the presence of highly annoying phenomena whereas $K < 5$ denotes the absence of squeak.
- *Relative RPM deviation* (*RRD*), defined according to [2]. The *RRD*, measuring the variation of the DC motor speed (i.e. RPM) during the stationary phase of the sound signal, represents an important metric for steadiness.

Moreover, the following psychoacoustic metrics were evaluated:

- *Loudness* It is currently considered the metric more closely related to the perception of the sound level. It is important to remark that the perception of loudness depends on source direction, bandwidth, frequency content and signal temporal characteristics [17]. The approximation of loudness with the *SPL* is valid only for sinusoidal signals or narrow bandwidth and low levels. In the present study loudness time functions and their statistical distributions were evaluated. In particular, the following variables were computed: the total loudness *N*, defined as integral of the specific loudness according to the standard DIN 45631/ISO 532B; the percentile loudness N_i, i.e. loudness value reached or exceeded in *i*% of the