MADRID
inter.noise 2019
June 16 - 19
NOISE CONTROL FOR A BETTER ENVIRONMENT

Sound Quality of Small DC Motors

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ABSTRACT

Many industrial and consumer applications require movement between their components to achieve the desired functionality. In most cases, movement is obtained through the use of gearmotors, which allows to adapt speed and torque to the requirements established during the design process. As a general rule, gearmotors comprise a motor, which acts as the main energy source; and a kinematic chain, which is responsible for transmitting the movement towards the output shaft by modifying the input torque. The motor is one of the most important noise sources in gearmotors and, therefore, its selection largely determines the acoustic behaviour. Throughout this work, it is carried out the study of the sound quality of small electric motors with the aim of establishing a metric that facilitates, during the design process, the selection of the most suitable motor for its implementation in small electromechanical devices. For this purpose, a semantic differential method is adopted to evaluate user's perception according to different attributes, such as annoyance, power, robustness, functioning, loudness, price and quality.

Keywords: DC motor, sound quality, annoyance, pleasantness, noise
I-INCE Classification of Subject Number: 61

1. INTRODUCTION

Currently, there exists a great number of consumer products in the market which functionality depends on certain movement. In most cases, those devices are actioned using an electric motor, which represents near the 45% of the total electricity consumption of the market [1], and allows to transmit power and movement to other components within the device. An example of this kind of machines could be found in home appliances, electric hand tools, or even vehicles.

It is possible to classify the motors regarding the supply needed for its operation: direct current (DC) and alternating current (AC). Nowadays, there are different models of DC motors, being the brushed one the most common. Motors could be divided in two main parts. On the one hand, we find the static part of the frame, called *stator*. On the other hand, we have the *rotor*, which is an internal part whose rotation is transmitted through the output shaft.

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The interaction between the magnetic flows from rotor and stator give rise to the electromotive forces responsible for the movement. For this kind of motors, the connexion between *rotor* and *stator* takes place by means of brushes sliding on the surface of the commutator. The brushes wear out over time and therefore, it requires periodic maintenance. In order to figure out this problem, during the last years, the use of brushless motors has been considerable increased. Its low maintenance represents a considerable advantage over other models. Likewise, last advances in electronics have promoted the use of stepper motors and servomotors. With these devices, speed and position can be controlled more precisely.

Engines have mobile elements and therefore, they are susceptible to generate noise and vibrations. The main causes of noise in motors can be divided into two groups: on the one hand, those with a magnetic origin as magnetostrictive or electrostrictive effect; and, on the other hand, those noises caused by the frame, the shafts or the bearings, and whose origin is mechanical.

The noise emitted by and electric motor is formed by a large number of harmonics, being the first one related to the rotating speed and the number of poles that compose the device [2]. According to Zwicher et al. in [3], sound with a spectrum rich in harmonics could be perceived by the listener as roughness. In the same way, these components will affect the perception of tone [4]. Many of the existing works on the literature regarding the noise generated by motors focus on monitoring the operating status of the samples. Fault detection is a key factor for industrial applications where an early detection of the defect can avoid unnecessary operational or maintenance costs. There are some different alternatives to carry out this kind of controls. Liu et al. in [5], by means of a literature review, describe the more widespread techniques for induction engines. Thus, we can distinguish between the use of parameters, the frequency domain analysis, transient analysis, order analysis, envelope analysis, etc. In the same way, Glowacz et al in [6] present an early fault diagnosis technique based on signal recognition for induction motors.

Focusing on domestic environment, subjective perception of consumers becomes more relevant, being determinant to establish the quality of a product. The engine is one of the most important noise sources in consumer applications. Therefore, a better understanding of its behaviour could be useful during the phase of product design and development. In this sense, Raffaele Dagonetti et al. in [7] carry out a psychoacoustic study to evaluate the noise emitted by different DC motors. For that, the authors evaluate six different models using the paired comparison method. The tests analyse aspects such as tone, roughness or annoyance, surveying a total of 115 people. Authors conclude that tone is directly related to the number of slots in the winding. At the same time, the results show a relationship between the annoyance perceived by the listeners and the tone or the roughness. The work highlights the need for further testing to analyse new parameters that can predict in a better way the consumer perception.

The goal of this work is to establish a metric that facilitates, during the design process, the selection of the most suitable motor for its use in small electro-mechanical devices. First, the acoustic behaviour of different motors is studied. Then, psychoacoustic tests are performed using the semantic differential method. Finally, it is obtained the most relevant parameters describing the sound quality of the samples from the correlation between subjective perception and objective analysis.

2. MATERIALS AND METHODS

2.1 Samples

So as to carry out this study, seven different DC motors where selected (figure 1). Table 1 includes the main properties of each sample.

Figure 1. Some of the DC Motors used in the study.

Tablee 1. Mechanical and electric parameters of the samples.

Sample	Voltage (V)	Speed (rpm)	Current (A)	Max. Torque (g·cm)
S1	12	4000	0.23	195
S2	12	4000	0.17	166
S3	24	4000	0.07	204
S4	24	4000	0.08	171
S5	12	4000	0.17	160
S6	12	3500	0.12	164
S7	12	4650	0.17	168

2.2 Sound Sample Acquisition and Analysis.

Sound sample acquisition was conducted in a semi-anechoic chamber using a calibrated microphone placed 10 cm away from the engine. The recordings were 15 seconds long.

For each sound, the Sound Pressure Level, SPL, was calculated. At the same time, traditional psychoacoustic parameters - loudness, sharpness, roughness, fluctuation strength and tonality - and some compound metrics – sound pleasantness and objective annoyance - were obtained.

Actually, motors are part of a whole and therefore, they interact with other components. In order to analyse how boundary conditions affect their acoustic behaviour, six of the samples were fixed to a small structure and measured again.

2.3 Auditory Tests Setup.

In order to establish the sound quality of the motors, auditory tests were carried out using the noise recorded from each sample. The study was conducted by the semantic differential method, analysing the subjective perception of listeners according to different attributes: annoyance, hardness, power, functioning, loudness, price and quality. Tests were conducted in a laboratory by means of headphones. In order for the samples to be evaluated, participants made use of a software tool specially designed for this study.

Listeners should indicate, through a scroll control, the value they perceived for each adjective (see figure 2).

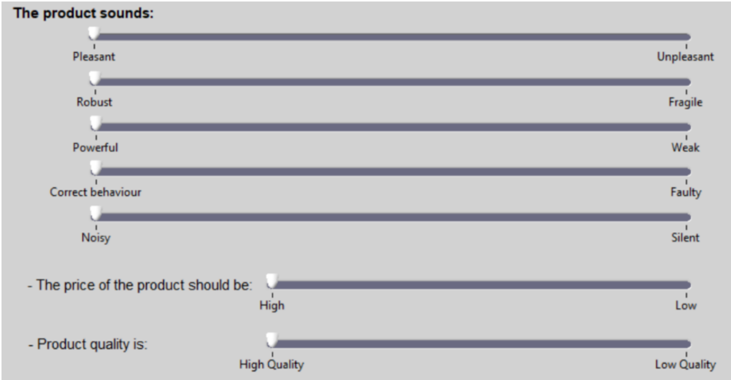

Figure 2. Software develop for the auditory tests.

The average value for each sample and attribute was calculated from listener's responses. Subsequently, the results were correlated with the objective metrics described in section 2.2.

3. RESULTS

3.1 Acoustic behaviour of DC motors

Noise produced by DC motors was characterised by the presence of a large number of harmonics. As described in section 1, these frequencies were associated with characteristics like rotation speed or the internal composition of the samples. For that reason, the frequency spectrum varies from one sample to another. Figure 3 shows the spectral response obtained in each case.

Different parameters were calculated for DC motors. Table 2 shows the values obtained for the sound pressure level and the psychoacoustic parameters. The results revealed a considerable difference in the SPL between samples (maximum difference of 9 dB). The same behaviour is observed for other metrics like tonality and roughness. According to the objective annoyance, the engines with high loudness should be perceived as more annoying.

Table 2. Acoustic characteristics of different samples.

	S1	**S2**	**S3**	**S4**	**S5**	**S6**	**S7**
SPL, dB(A)	54.8	52.4	59.0	58.2	61.4	54.2	57.6
Loudness, sone	8.71	6.84	10.03	10.61	11.11	7.37	9.08
Sharpness, acum	2.32	2.82	2.98	2.55	2.98	2.62	2.78
Fluctuation Strength, vacil	0.04	0.06	0.08	0.03	0.05	0.05	0.03
Tonality, tu	0.85	1.70	1.02	0.59	1.33	1.06	1.09
Roughness, asper	0.84	0.94	1.38	1.81	1.66	1.24	1.02
Objective annoyance, a	24.85	19.98	44.26	37.46	42.28	22.12	28.36
Pleasantness, pu	0.18	0.11	0.06	0.06	0.05	0.11	0.10
10% Loudness	9.02	7.11	12.13	11.66	11.93	7.86	9.26

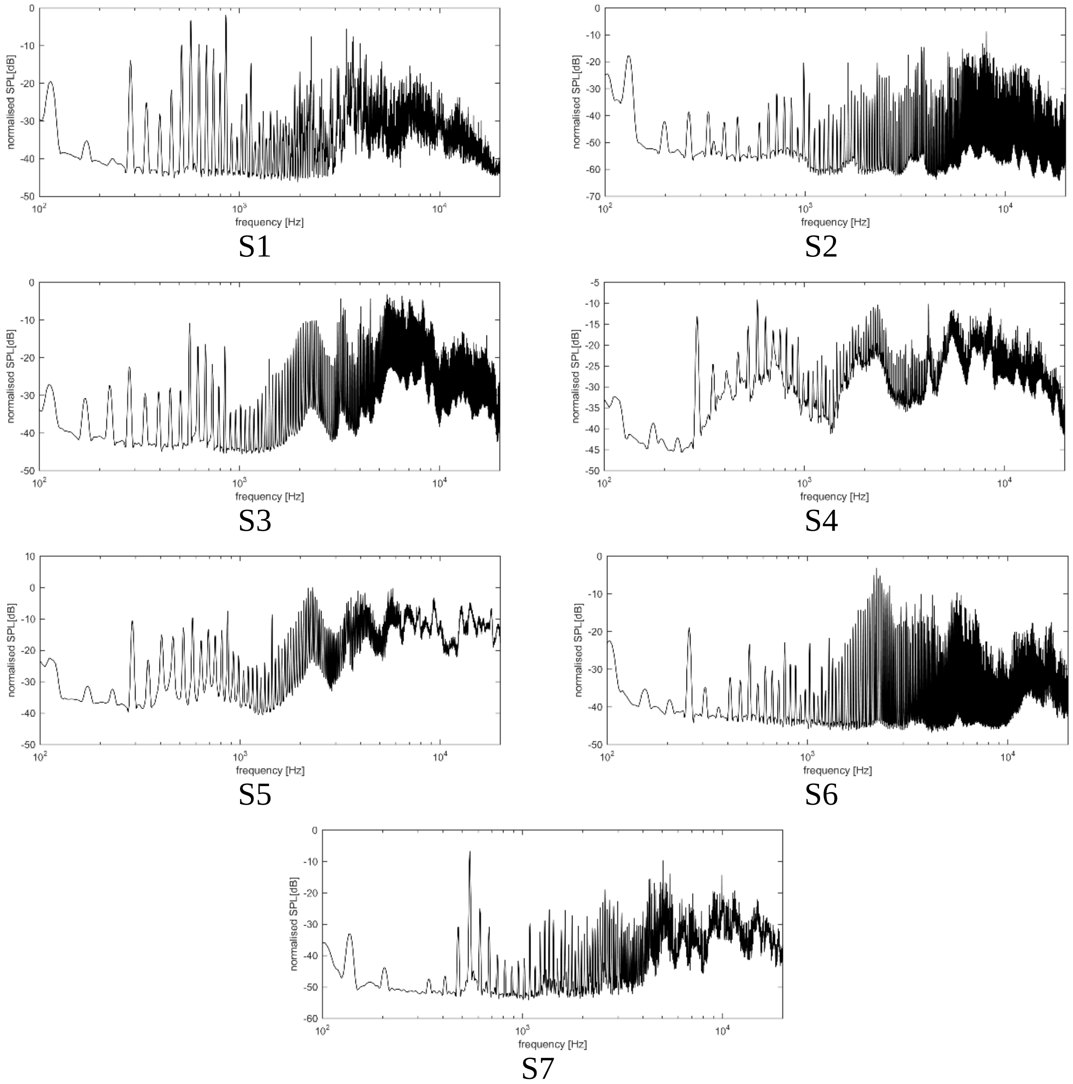

Figure 3. Frequency spectrum obtained for each sample.

The acoustic behaviour of the samples changed significantly when being fixed to the structure. In most cases, the sound pressure level decreased as a consequence of a higher rigidity (see figure 4). On the contrary, other samples became noisier due to the structure radiation. This change in the acoustic behaviour is also reflected in the psychoacoustic parameters, especially in those related to the sound level of the motors.

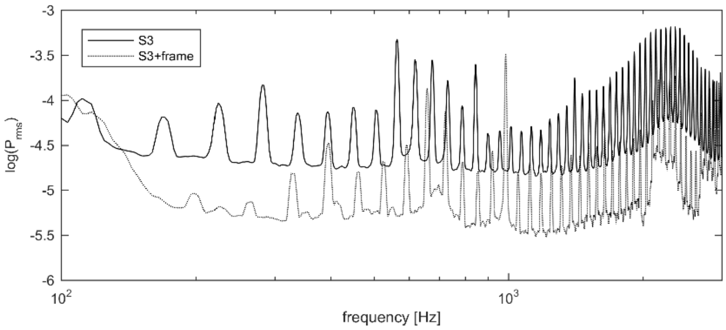

Figure 4. Comparison between frequency spectrum for free and fixed conditions. Sample S3.

3.2 Sound quality evaluation

The auditory test was conducted on a group of 17 people with ages ranged between 20 and 57 years old. All the listeners participated voluntarily, being most of them students from the University of Alicante.

The average value of each attribute was calculated taking into account the preferences of all the subjects. Figures 5 and 6 show the differences obtained between samples and attributes for motors under free condition.

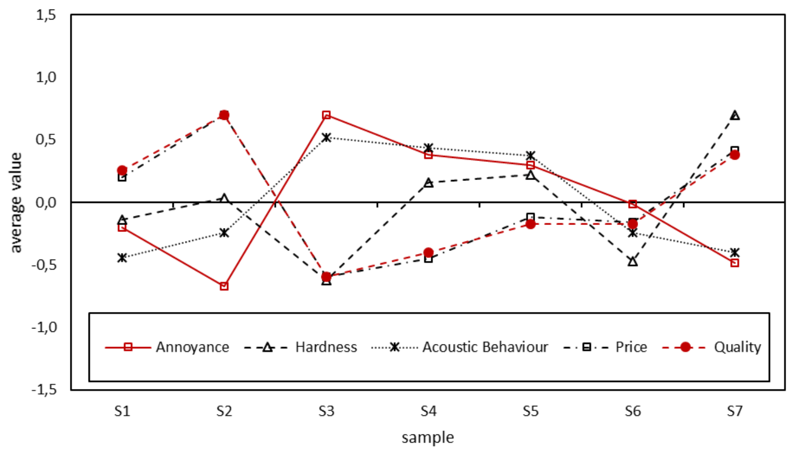

Figure 5. Average values obtained for some attributes included in the auditory tests.

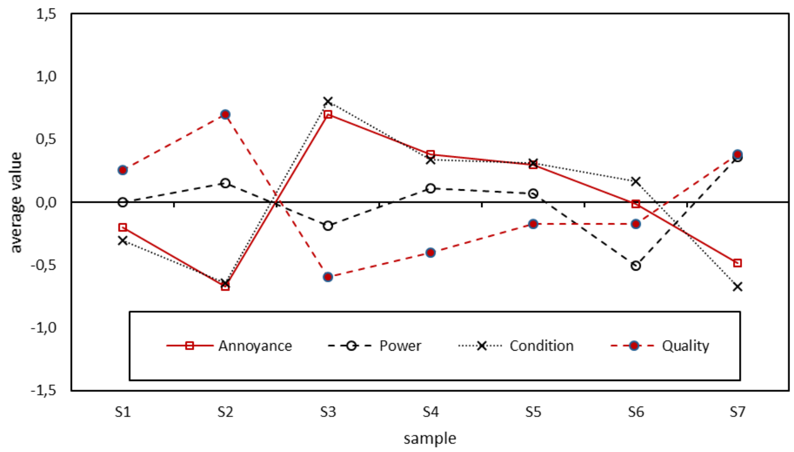

Figure 6. Average values obtained for attributes annoyance, power, condition and quality, included in the auditory tests.

According to the listener's perception, there was a relationship between some of the attributes evaluated during the auditory tests. Annoyance caused by the noise radiated by the motors showed a high correlation both with the condition of the samples and their acoustic behaviour (noisy-silent). Contrarily, it provided an inverse result compared with quality and price of the product. The same trend was observed for the functioning of the motors and their acoustic behaviour. Malfunction or noisy samples were associated with low levels of quality and at the same time with low prices. Likewise, the results showed a relationship between hardness and power of the samples. Finally, as it is shown in figure

7, there was a high correlation between the judgements of the listeners in terms of product price and quality.

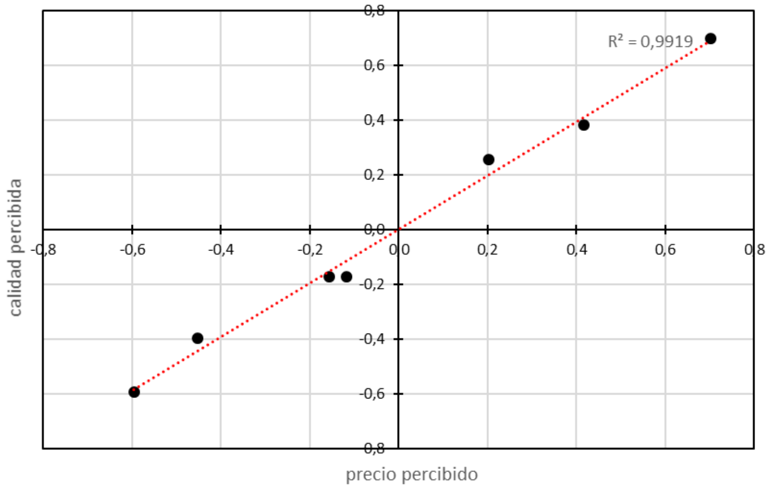

Figure 7. Relationship between the quality and the price perceived by listeners.

Analysing the correlation between subjective perception and objective parameters, it was observed a good relationship between metrics like roughness or 10% loudness and the perceived annoyance, the acoustic behaviour of the samples, their price or their quality. In the same way, the annoyance perceived by the listeners was correctly described by the objective annoyance defined by Aures (0.86). The same results were observed for the acoustic behaviour (90%) and the total quality of the samples (76%). On the other hand, it should be noted that, according to listeners, none of the parameters were able to describe the power perceived. Regarding the hardness of the product, according to the Pearson's correlation coefficient, only the fluctuation strength provided significant results.

Comparing the results with those obtained under fixed conditions, the variations of the acoustic behaviour had certain influence in the subjective perception derived from the auditory tests. Figure 8 shows a comparison between the average annoyance and sound quality for free and fixed conditions.

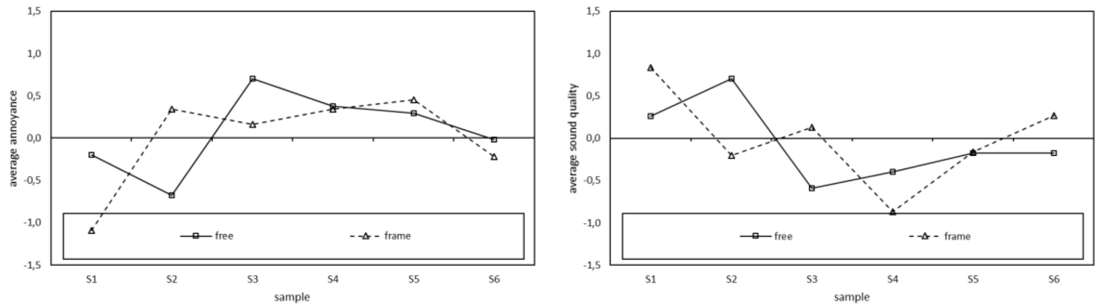

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Figure 8. Comparison between free and fixed conditions. (left) Subjective annoyance. (right) Subjective sound quality.

Once the motors were fixed to the structure by its front, annoyance was described by SPL (0.80) and loudness (0.82). To a lesser extent, listener's perception regarding this attribute could be explained by the parameter objective annoyance (0.77). This comportment is repeated for the acoustic behaviour attribute. Fixing the motors, neither the hardness nor the power showed an explicit relation with the psychoacoustic parameters used in this study. Regarding the functioning of the samples, the roughness seems to be the key to describe the preference of users. Price and quality, according to Pearson's correlation coefficient, were described by tonality and roughness (around 0.75).

4. CONCLUSIONS

The current study aims to determine the acoustic behaviour of small electric motors and the subjective perception of consumers in relation to a number of attributes. So as to do this, the noise emitted by different samples was acquired and analysed using acoustic parameters. The results showed a frequency spectrum formed by a large number of harmonics. At the same time, it was observed a significant difference between the sound pressure level of the samples. This behaviour was repeated for other parameters, especially for roughness and tonality.

Following, the sound samples were used to carry out auditory tests by means of the semantic differential method. The results showed an important correlation between some of the attributes evaluated by the listeners, highlighting the relationship between annoyance, functioning, price and quality. Similarly, some of the psychoacoustic parameters described adequately the user's perception. In this way, roughness and loudness seemed to be key factors to define the subjective annoyance, the price or the quality of the product working as a standalone device. However, a change in the boundary conditions of the samples led to a variation of their acoustic behaviour and hence, of the listener's perception. In this case, annoyance was better described by means of SPL and Loudness. On the other hand, the price and quality established by the users were represented by the roughness and tonality, which is consistent with previous results found in the literature. The use of more complex metrics, formed by a combination of different parameters, could lead to a considerable improvement of the description made by the listeners.

5. ACKNOWLEDGEMENTS

The authors thanks all those who participated in the auditory tests, especially students from the Universidad de Alicante.

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