Applied Acoustics 119 (2017) 108–118

Contents lists available at ScienceDirect

Applied Acoustics

journal homepage: www.elsevier.com/locate/apacoust

Pairwise comparison psychoacoustic test on the noise emitted by DC electrical motors

Raffaele Dragonetti [a,*], Michela Ponticorvo [b], Pasquale Dolce [b], Sabato Di Filippo [a], Francesco Mercogliano [c]

[a] University of Naples Federico II, Department of Industrial Engineering, Naples, Italy
[b] University of Naples Federico II, Department of Humanistic Studies, Naples, Italy
[c] DENSO Thermal System S.p.A., Poirino, Italy

ARTICLE INFO

Article history:
Received 23 June 2016
Received in revised form 22 December 2016
Accepted 26 December 2016
Available online 3 January 2017

Keywords:
Pairwise comparison
Roughness
Pitch
Annoyance
Psychoacoustic
Electrical motor

ABSTRACT

In this paper, the noise emitted by cheap DC electrical motors is investigated by means of a one-to-one comparison psychoacoustic test. This is because, nowadays, DC electrical motors are widely used, and it is useful to understand the main causes of acoustic annoyance. In particular, though different DC electrical motors are fed with a power generator whose voltage is kept constant, their noise emissions are different, indicating various emission spectrums. Since a spectrum is characterized by many harmonics related to the rpm of motors, one of the main problems is finding a method to understand how these harmonics are related to sound quality parameters and, therefore, acoustic annoyance.

Two descriptors of sound quality, roughness and pitch height, have been studied. Furthermore, the manner in which roughness and pitch height affect the annoyance is investigated.

Results of this study can help manufacturers and users discard motors on the basis of their noise before being sold or installed.

1. Introduction

Nowadays, many machines are driven by small DC permanent magnet motors because they are lightweight, compact and cheap. For example, inside a car, they are used to drive the HVAC systems (Heating, Ventilation and Air Conditioning), windshield wipers, antenna lifts and power windows. Even if the sound level of noise emitted by the latter is generally low, in a quiet environment, it can become the main source of perceived noise, creating acoustic discomfort. This is the case for electric vehicles, where internal combustion engines have been replaced by electric motors. At low speed, the aerodynamic or tyre/road noise are negligible [1,2] with respect to the internal source of noise that may be annoying if not carefully treated.

Noise radiated by a small DC permanent magnet motors can be attributed to several factors. Shaft bearings (due to misalignment), improper lubrication and loose bearings can cause vibration that is transferred to the vibrating surfaces of the motor and causes noise. Another cause of noise is produced by the undesirable radial magnetic forces generated with the tangential forces in the air gap between the motor and stator. While the tangential forces are responsible for the movement of the rotor because they generate a moment force (torque), radial magnetic forces cause the so-called "cogging torque". Depending on the mounting system, these forces can manifest themselves as a vibratory force at the motor mounting site. Therefore, they are a further structural-born source of noise [3,4]. Brushes, if present, are another source of noise.

End-of-line quality assessments [5,6] and internal specific quality control of manufactures pose the attention of the global SPL emitted by the latter or at least of the sound level evaluated on the specific harmonic emission. Often, a DC electrical motor is judged to be discarded or not from an acoustic point of view if the measured SPL is bigger than a specific threshold; however, a thorough analysis of the sound quality of the noise should be performed.

In particular, noise radiated by a DC electric motor is a complex tonal signal, where the first harmonic (hereafter indicated f_M) is related to the rpm of the rotor and the number of poles [4]. The amplitudes of the subsequent harmonics are strictly related to the motor depending on a combination of all the causes described above, and they can change considerably from one motor to another of the same family. It was observed that the spectrum is populated by almost all subsequent harmonics of f_M. However, the level of the individual components is not constant in time, and the frequency associated with these harmonics also varies,

* Corresponding author.
E-mail address: dragonet@unina.it (R. Dragonetti).

http://dx.doi.org/10.1016/j.apacoust.2016.12.016
0003-682X/

especially those with high frequency. Due to the large amount of harmonics, the main parameters related to the noise annoyance, estimated from the noise radiated by the tested motor, do not change considerably between one motor and another. However, a preliminary listening test was carried out to understand which attributes among loudness, sharpness, pitch height and roughness affects more auditory perception of noise emitted by motors. This test revealed that the pitch height and roughness are the main parameters of sound quality that characterize the differences among engine emission. It is noteworthy to underline that, though the loudness is ruled out as major factor, this does not imply that it is an important parameter as indeed highlighted in previous studies [7,8]. The observed differences stimulated authors to conduct a psychoacoustic test to investigate the ability of the listener to distinguish motor roughness and pitch. Furthermore, the psychoacoustic test was meant to compare the subjective perception of motor annoyance related to roughness and pitch to understand if these two parameters, alone, can explain differences of annoyance. For this reason, the signal of the noise radiated by the motors was not loudness-equalized as suggested by Susini et al. [7].

Complex tones are perceived as rough due to the effect of beats between the component tones [9]. Due to harmonic fluctuation, the perceived roughness is also correlated to carrier frequency and modulation frequency [10]. Besides, a complex sound is perceived as more rough if the fundamental frequency has a low value [11].

Tonal components affect different aspects of the pitch perception – in particular, the pitch height (often indicated as f_0), pitch strength and pitch chroma [12]. In this paper, attention was paid to pitch height rather than tonal characteristics expressed by Aures (i.e., tonality [13]).

The pitch height, often simply called pitch, is due to low- and high-order harmonics. The mechanisms underlying the pitch perception of a complex tone have long been studied [14,15], providing insight to peripheral auditory systems. It seems to be divided into two correlated types of cues: place cues, dependent upon frequency selectivity, and temporal cues, dependent on neural phase locking. When a complex tone contains a resolved harmonic (the first 10/11 harmonics [16,17]) due to the spatial separation of frequency components along the cochlear partition, its pitch (or height pitch) can be evaluated by matching the pattern of activity across a tonotopic neural map [18–21]. On the other hand, when high-order harmonics interact within single auditory filters, they become unresolved; therefore, harmonic template models are not applicable. A combination of unresolved harmonics has a period which is reflected in a neural phase locking and can be extracted by an autocorrelation-type mechanism [22–26]. In general, the pitch strengths are weaker than that based on resolved harmonics and more dependent on phase relationships among the partials. Hence, tonal components influence the roughness and pitch they make noise more annoying [9,13,27].

The test was carried out in an early stage without any product (e.g. fan, drive belt) to not modify the spectrum emission and consequently the pitch/timbre and roughness. The participants were first trained to distinguish these variables in motor sound and were then asked to evaluate motor roughness, pitch and annoyance with a one-to-one comparison. In this context, it is indeed relevant to analyse not only the objective variables related to sound but also their subjective perception and relation between objective and subjective methods of measurement.

A psychoacoustic test also serves to understand if the main source of annoyance can be explained by these two quantities. Even if, as previously stated, these quantities are strictly correlated to the sensation of annoyance, with the help of this test, it is possible to understand how small or large differences (if any) can affect the annoyance for this type of "technical sound". The main result of this work is to give a guideline to determine whether a harmonic component affects the pitch and roughness and how it can be annoying in a global sound judgment.

The paper is organized as follows. In Section 2, a description of electric motors and their sound emission is introduced. In Section 3, all details about the psychoacoustic test are described. Finally, Section 4 reports the results and discussion about the psychoacoustic test.

2. Electric motor and sound emission

In this section, a mechanical description of the electric motor, details about measurement and sound emissions are given.

2.1. Description of the electric motor

The object of this work is a brush DC motor with 12 V and 450 W maximum power reported in Fig. 1. Its rotor is composed by a shaft and an armature core with 12 skew slots that contain the winding. The rotor is connected to the motor body by two bushes that allow for rotation without friction. On board of the body, there are two permanent magnetic poles and a brush holder. The electric connection between rotor and stator is realized by brushes that slide on the commutator surface splined on the bottom side of the shaft. From an acoustic point of view, the noise mentioned in this work is caused by the interaction of the bushes with the commutator's vanes; for each rotation, a "vane jump" (an impact of the bushes with the vanes' surface that generates noise emission) occurs.

2.2. Noise emission

Measurements are performed in a silent anechoic room. Before performing measurements of noise emitted by electric motors, the SPL of environmental noise is less than 10 dB starting from 20 Hz. Forty-five electric motors are fed with a power generator whose voltage is kept constant at 3.5 V and measured with a microphone at 10 cm from the centre of the shell. The frequency distance among harmonics is about 17 Hz, which corresponds to the first harmonic f_M. Hereafter, electric motors will be labelled as Mot00, ..., Mot44. It is worth noting that the aim of this procedure is not to completely characterize the acoustic behaviour of electric motors but to have a comparison among noise measurements emitted by the latter. Thus, they are elastically suspended to avoid any transmission of vibration which, in turn, may radiate sound. Fig. 2 reports a typical 3D surface spectrogram computed on the sound pressure signal of Mot00.

The spectrum is harmonic, where the first harmonic f_M is related (in a constant speed condition) to the rpm of the motor [4]. As it is possible to note from Fig. 2, apart from large fluctuations, each harmonic is characterized by a sawtooth profile whose period of oscillation is related to the period $1/f_M$.

Moreover, the harmonics characterized by high frequency are not stable, and it is possible to observe a small fluctuation in frequency of about 2–3 Hz. From 45 measurements, six motors are randomly drawn, and Table 1 reports the main psychoacoustic parameters evaluated by the dedicated software package of Labview.

Loudness values are obtained by using the ISO 532B standards [28], sharpness and tonality values by using the Aures method [10], and roughness values by using another Aures method [29].

From Table 1, it is possible to note that, except for small variation, all parameters are quite equal. As an example, Fig. 3 reports the average spectrums of Mot12 and Mot42.