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Technical note

An experimental analysis of the methods for brake squeal quantification

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ABSTRACT

The present paper analyzed 6 brake noise indexes (or Squeal Indexes) in order to assess the squeal produced by 4 different pad materials, which were subjected to dynamometer tests in accordance with SAE J2521 test procedure. Regardless the rating system used in the analysis, the same ranking was obtained with respect to the amount of noise produced by the brake pads selected in this study. Results from the noisiest to the quietest friction material were: pad 1 (semi-metallic) > pad 4 (low-metallic) > pad 2 (Non-Asbestos Organic) > pad 3 (a low-metallic). Besides, Squeal Indexes 2, 3 and 4 (SI_2, SI_3, and SI_4) have shown the best ability for distinguishing friction materials with respect to the amount of brake noise. These rating systems are among the simplest methods to implement, since they consider a maximum of 2 or 3 input parameters. Finally, the histograms of friction coefficient have shown that the noisy stops have a higher average level of friction than the average result obtained for all brake stops.

1. Introduction

Brake system is a critical safety component for vehicles, since it is responsible for reducing the car's speed, avoiding a crash [1]. Friction contact between pad and disc produces the force necessary to reduce the speed of the vehicle, converting the kinetic energy into heat, vibration and noise [2].

Although brake noise and vibration represent only a small fraction of the total braking energy, it can produce high sound pressure levels, causing acoustic discomfort to the car drivers [3,4].

The annoyance caused by brake noise is not the only problem. Car owners have often associated noise and vibration produced during braking as a symptom of failure in the brake system [4–8]. This situation may cause irreparable damage to the automobile brand [7,9]. For this reason, brake noise complaint is considered one of the most important warranty issues for carmakers and brake manufacturers [10]. As pointed out by Papinniemi et al. [11], the occurrence of brake squeal is a concern because it causes significant discomfort to the vehicle occupants, and leads to customer dissatisfaction, increasing warranty costs. However, in most of the cases brake noise has little or no effect on the braking performance [12–14].

Among many brake noises described in the specialized literature (e.g. judder, creep-groan, moan, howl, wire-brush, squeal, squeak e squelch), squeal is often listed as the most problematic one [4,13]. Squeal is a high frequency (1–20 kHz) vibration of brake system components during a braking action resulting in noise audible to vehicle occupants and passers-by [4]. Despite enormous research and engineering effort [e.g. in 9,15,16], still today there is no any technique able to completely suppress squeal noise from brake systems [4,17].

Laboratory testing procedures have been largely employed by research institutes and industry aiming to study the squeal produced by brake friction materials [18]. In this context, the inertia dynamometer has stood out as one of the most reliable methods available. According to Papinniemi et al. [19], this machine can accurately represent the braking performance of a vehicle. Besides, dynamometer tests have become a standardized test method in industry, with many international testing procedures. One of these standard methods, the SAE J2521 [20], describes the recommended practices for a squeal noise dynamometer test. This standard is accepted worldwide and mainly used in Europe [21].

In addition to the recommended practices, it is also necessary to define a proper rating system for measuring the amount of brake noise produced by different friction materials. Several noise indexes are shown in the literature, e.g. in Eriksson [3], Oberst and Lai [7], Abendroth et al. [21], Suetti [22]. Each rating system considers different parameters in the noise index (or Squeal Index - *SI*) calculation.

However, each of these rating systems has been discussed and validated in separate studies. It means that the different Squeal

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Indexes have never been compared under a common basis, i.e. they have never been analyzed using the same test procedure, while keeping fixed both the brake materials and the testing machine.

The present research paper aims to evaluate the main indexes for brake noise assessment by using a common basis for comparison. Special attention will be given to the ability each rating system has to distinguish the amount of brake noise produced by different friction materials. To make this possible, 4 different brake pads were subjected to the same the test procedure, the standard SAE J2521 [20]. After the experiments have been completed, each Squeal Index was determined, and a discussion of the main results is presented.

2. Experimental test setup

The experimental procedure carried out in this study was based on the SAE J2521, 2006. From the total of 2377 stops described in this standard, 460 stops correspond to the cold drag module, which was not run in this work.

The inertia dynamometer used to perform the brake squeal matrix (model 3900, made by *Link Engineering Company*, USA) was designed for performance, and NVH (Noise, Vibration and Harshness) testing applications. This dynamometer contains an environmental chamber, which controls temperature e humidity [6]. Instrumentation of the test chamber includes a microphone, which is positioned in the vertical plane and perpendicular to the brake axis. Besides, the microphone is pointing downwards. All recommended practices described by SAE J2521 [20] were carefully taken into account in the tests conducted in this study.

Four different brake pads (see the formulation in Table 1) were used in the braking tests carried out in this study.

The rotor used as a counterpart in the experiments was a solid brake disc, made of grey cast iron and composed of 3–4% C, 1–2% Si and Mn and 1% of trace elements. All the 4 pads and the brake disc are standard components used in commercial light vehicles. Brake pad 3 and 4 are low-metallic (low-met), pad 1 is a semi-metallic (semi-met), and pad 2 is a Non-Asbestos Organic (NAO).

3. The Squeal Indexes

Six different Squeal Indexes (*SI*) were analyzed in the present study. Each rating system considers a different set of parameters, as shown in Table 2.

3.1. Squeal Index 1 (SI_1): SAE J2521

Squeal Index 1 (SI_1) was based on the test procedure described in SAE J2521 [20]. Mathematically, SI_1 is a result of the number of noisy brake events (N_{noise}) divided by the total number of stops (N_{Total}), as shown in Eq. (1).

$$SI_1 = \frac{\sum N_{noise}}{N_{Total}} \tag{1}$$

3.2. Squeal Index 2 (SI_2): objective noise index - ONI -A

ONI-A is determined by giving weighting factors (W_i) to different stop groups, which are rated according to the range of sound pressure level (SPL), as shown in Table 3 [7,22,23].

The calculation procedure of the Squeal Index 2 is shown in Eq. (2).

$$SI_2 = \frac{\sum_{i=1}^{7} (W_i N_{noise})}{N_{Total}} \tag{2}$$

where SI_2 is the Squeal Index *2* [%], W_i is the weight used for a certain SPL *i* [–], is the number of noisy brake events within the range of SPL *i* [–], and N_{Total} is the total number of stops [–].

3.3. Squeal Index 3 (SI_3): Oberst and Lai

Oberst and Lai [7] proposed to quantify the brake squeal through the integral (area) of the curve that represents the percentage of noisy brake events (N_{Noise}) versus SPL. According to the authors, SI_3 is obtained by multiplying the number of squealing frequencies or peaks (p) found in the sound spectrum by the numerical result of the area under the N_{noise} versus SPL curve, as shown in Eq. (3).

$$SI_3 = pA_{(N_{noise})VS(SPL)} \tag{3}$$

where SI_3 is the Squeal Index 3, p is the number of squealing frequencies found in the sound spectrum, $A_{(N_{noise})VS(SPL)}$ is the area under the curve of N_{noise} versus SPL.

3.4. Squeal Index 4 (SI_4): Eriksson

SI_4 consists of capturing the instantaneous value (snapshot) of the SPL (in dB (A)) at a given time interval during the stops. An occurrence of squeal is registered if, during the snapshot, the instantaneous signal of SPL is equal to or greater than 70 dB(A). This way, a single braking operation can have more than one noise event.

Mathematically, the Squeal Index 4 (SI_4) is the result of the summation of the number of snapshots registered as noise occurrences (S_n) divided by the total amount of snapshots (S_T), as shown in Eq. (4). A time interval of 1 s between the snapshots was used in this analysis.

$$SI_4 = \frac{\sum S_n}{S_T} \tag{4}$$

3.5. Squeal Index 5 (SI_5): Suetti

The Squeal Index 5 (SI_5), proposed by Suetti [22], attributes 10 ($I_{max} = 10$) as the maximum value for a completely quiet braking operation. Six different loss factors are applied to I_{max}, as shown in Eq. (5).

$$SI'_5 = I_{max} - I_{SPL} F_f F_a F_T F_S F_D \tag{5}$$

Table 1
Approximate formulation of the brake pads.

Categories	Pad 1 Semi-met (%)	Pad 2 NAO (%)	Pad 3 Low-met (%)	Pad 4 Low-met (%)
Reinforcing fibers	50	15	25	29
Organic additives	14	12	11	6
Lubricants	21	13	27	35
Abrasives	7	10	4	8
Fillers	8	50	33	22