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Evaluation of sound quality in a tractor driver cabin based on the effect of biodiesel fatty acid composition

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HIGHLIGHTS

- Biodiesel chemical composition affects sound quality and engine comfort.
- Characterization of sound quality in a driver cabin of a tractor has been performed using a scale model.
- A strong correlation between engine power, loudness, cetane number and unsaturation degree has been found.
- Considering cetane number and viscosity, loudness shows the opposite effect to roughness.
- A good sound quality requires a compromise between biodiesel viscosity and cetane number.

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ABSTRACT

Nowadays, one of the main concerns for vehicle customers is comfort. This fact, together with the constraints imposed by legal regulations on noise emissions and human exposure to noise, have led to consider noise and vibration among the most important design criteria for agricultural machinery cabins. In this context, experimental analysis procedures for rapid prototyping and prediction models for early design assessment are crucial. This work presents a study of sound quality inside a tractor cabin mock up when the engine is fueled with different biodiesel/diesel fuel blends. In this study, the influence of the chemical properties of biodiesel has been correlated to sound quality metrics, i.e. loudness and roughness, and thus, their influence on the comfort of the tractor driver cabin. It has been found that cetane number and unsaturation degree of biodiesel are strongly related to loudness, whereas viscosity and unsaturation degree are strong indicators of roughness. Finally, to predict loudness and roughness based on biodiesel chemical properties, surface response models have been developed.
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1. Introduction

Biodiesel has the opportunity to contribute to the gradual substitution of fossil fuels in order to achieve the 10% renewable energy target imposed by the EU [1]. An additional advantage of biodiesel utilization is its potential domestic application by farmers to operate their agricultural machinery.

One problem associated to drivers of agricultural machinery is the high noise and vibration levels to which they are often exposed. Subsequently, drivers are suffering from fatigue, hearing damage and other health problems [2]. In this sense, the design of the tractor cabin, following noise and vibration comfort criteria, may be an important factor to take into account by manufacturers. For these reasons, to provide the optimal cabin design, the assessment of conceptual design alternatives in an early design phase is required. In fact, in recent years, this practice has become extensively used, particularly in the automotive industry [3].

Some authors have found meaningful differences from the noise radiated by an engine depending on the fuel used. It seems to be due to the combustion process, that it is strongly dependent on the biodiesel chemical properties, which affect the fuel-burning rate and injection timing advance, among other parameters [4–7]. When combustion takes place, pressure and mechanical forces act over the engine block, producing the vibration of the block wall. In addition, the pressure gradients produced during combustion also cause the resonant oscillation of the gas in the combustion chamber [8,9]. It depends mainly on the bowl geometry and the gas temperature, being the last one dependent on the chemical properties of the fuel. The effect of engine vibration causes the

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cabin indoor noise by means of airborne excitation. Airborne excitation consists of sound that impinges on the exterior of the cabin and introduces cabin vibrations, which transmit sound to the interior. Therefore, it can be inferred that if fuel chemical properties, i.e. cetane number, cinematic viscosity, bulk modulus, iodine value or oxygen content among others, have influence on the noise radiated by the engine, thus they also may affect the noise perceived by the driver.

Although few decades ago research was focused on automotive noise reduction using active noise control techniques, nowadays efforts are mainly made to improve the sound quality inside the vehicle. Regarding this subject, research is mainly concentrated on the study of the radiated engine noise [10–12]. Since auditory impressions are subjective, different metrics are used to describe them [13–15]. In this sense, Sato and Miura [16] found out that comfortability in trucks running on diesel fuel is strongly related to Zwicker loudness. Moreover, Lee et al. [17] proposed to improve the combustion noise of an engine fueled with diesel fuel, considering its direct relationship with emissions. Although, these procedures are frequently used to study sound quality in an engine when it is fueled with diesel fuel, research concerning the influence of the chemical properties of biodiesel on sound quality in a tractor driver cabin is insufficient. Moreover, due to the EU legislation related to the increasing use of renewable energy, more research is needed.

For this reason, an experimental analysis for the evaluation of the airborne excitation in a tractor cabin model (based on sound quality metrics) for different biodiesel/diesel fuel blends at several engine operating condition has been developed. Moreover, the chemical properties of biodiesel blends have been correlated with the comfort inside the cabin using sound quality metrics. Finally, to find out the relationship between biodiesel chemical properties and the perception of noise in a driver cabin based on sound quality parameters, several simple response surface models have been proposed.

2. Experimental layout

In a previous phase, the noise radiated by the engine fueled with biodiesel blends and diesel fuel at several engine operating conditions was recorded. Next, recordings were used to both simulate the noise radiated by the engine and evaluate the effect of the use of biodiesel blends compared to diesel fuel on the perceived sound quality inside the tractor cabin. For this reason, a tractor cabin scale model was built.

2.1. Description of the engine set up

A four-stroke three-cylinder direct injection diesel engine from an agricultural tractor has been tested. The maximum torque provided by the engine was 162.8 Nm, achieved at 1300 rpm, while the maximum engine power was 44 kW at 2132 rpm (DIN 6270-A). The engine was coupled to a Froment XT200 electric dynamometer, being the maximum engine power 136 ± 1.44 kW of accuracy at 100% engine speed (provided by the National Institute of Agricultural Engineering, UK) [18].

For each fuel noise testing, different engine operating conditions following the 8-mode cycle, according to ISO 1878-4, were considered [18]. At the beginning, the engine was operated with straight diesel fuel, followed by the blends at 20% and 50% of methyl esters with diesel fuel. To check the influence of the fatty acid composition, biodiesel was made of olive pomace oil (OPME), palm oil (PME), sunflower oil (SME), coconut oil (CME) and linseed oil (LME). After each test, the engine fueling system was cleaned and the engine was stabilized to the new condition [19].

A Soundbook instrumentation series recorded the noise radiated by the engine, by means of a portable and multi-channel meter. The measuring device was a GRAS prepolarized free-field half-inch microphone. This system was equipped with the software Samurai v1.7 from SINUS Messtechnik GmbH (Germany). Recorded measurements were processed in Matlab R2008a, from MathWorks Inc (USA). The microphone was calibrated before each test using a B&K calibrator model 4321. Recordings were carried out following ISO 362-1:2007 and used to simulate the noise emitted by the scale model engine.

2.2. Description of biodiesel properties

In a previous work [6], the influence of the degree of unsaturation over emissions has been tested and analyzed. In this work, only the most popular biodiesel blends, according to the international market, have been selected. In this sense, 20% and 50% vo./vol. biodiesel/diesel fuel blends were produced and analyzed as commented in a previous work [6]. Some of the most important fuel properties are depicted in Table 1.

2.3. Tractor driver cabin scale model

The geometry of the tractor driver cabin scale model has been kept as simple as possible and following similar works [2,20]. The cabin scale model consists of two parts, the driver cabin (DC) and the engine compartment (EC), which are connected through a flexible joint allowing noise generated in the EC to be transmitted to the DC. A sound source placed in the EC is used to simulate a primary excitation disturbance source. This source is connected to a computer where the measurement of the noise radiated by the engine is stored. DC comprises five flat, rectangle shaped panels, stuck together as shown in Fig. 1. Panels present different thicknesses and are made of different types of plexiglass material to simulate the diverse structural parts of a cabin (roof, floor, doors, windshield, etc.), each one showing different dynamic properties. Material properties are summarized in Table 2. EC consists of four wood panels, as described in Table 2. The cabin mock up is placed in a wrinkled rubber mat, placed inside a semianechoic test room, as shown in Fig. 2.

One microphone is placed inside the cabin at 130 cm height, 71 cm distant to the front part of the cabin and 61 cm distant to the left side. The characteristics of the microphone, calibrator and the measuring equipment are detailed in Section 2.1.

2.4. Noise characterization

As previously mentioned, sound quality is related to the human appreciation of a certain audio stimulus. Psychoacoustics go beyond the mathematical interpretation of pressure signals, correlating acoustic stimuli with hearing sensation [20].

As a first step, the most appropriate set of metrics needs to be defined. In the present work, the procedure described in ISO 532B was followed [21]. According to this procedure, the specific loudness is presented in Sone/Bark units. It is important to notice that loudness and roughness are the most common metrics to describe engine noise [22,23], being specific and Zwicker loudness used to evaluate subjective perception of noise by the human ear. Zwicker loudness is defined as the integral of the specific loudness over Bark and is expressed in Sone. Roughness is related to high frequency modulation of the sound and its unit is the Asper. In this work, roughness has been calculated according to the model proposed by Aures [24].

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