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A Study on Modern Diesel Engine Combustion Noise

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Abstract—*Combustion noise in passenger cars powered with direct injection (DI) diesel engines is frequently the main reason why end-users are reluctant to drive this type of vehicle. Thus, the great potential of diesel engines for environment preservation due to their lower CO_2 emissions could be missed. This situation worsens with the current design trends (engine downsizing) and the emerging new diesel combustion concepts which are intrinsically noisy. This negative feature can be even more critical in transient operation due to the contribution of the temporal changes of both source and transmission path on engine noise. Therefore, combustion noise must be considered as an additional essential factor in engine development, together with performance. Thus, suitable design procedures are discussed in this paper. Regarding this study, most of the work available in the literature addressed combustion noise at steady operation.*

Keywords: *Combustion noise, Diesel engine, Emissions*

1. INTRODUCTION

Recently, the market for diesel-powered vehicles in India has experienced a notable increase for various reasons that are related to the high degree of development reached by this type of engine in recent years. The diesel engine is an environmentally friendly engine because of its fuel economy and the subsequent CO_2 emissions reduction. In addition, novel technologies for combustion control and exhaust gas after-treatment continue to develop to comply with emissions legislation. Taking advantage of these technologies, a great improvement in performance and driveability has also been achieved by diesel engines in recent years. However, diesel engines have faced serious acoustic problems. Due to the characteristic diesel combustion noise, the engine is considered to be the main source of noise in diesel-powered vehicles (Jenkins, 1975; Parizet et al., 2004). For that reason, car manufactures have devoted significant efforts to diminish Diesel engine noise (Challen and Croker, 1990; Russell, 1973). Split injection in automotive DI diesel engines made it possible to control combustion noise by actuating directly on the source (Gaffarpour and Noorpoor, 2007; Win et al., 2005). Despite these efforts, current designs are still too noisy, especially during transient operation. In these conditions, engine noise is not comparable to that radiated in steady operation, since several variables governing the combustion law and hence the noise source are changing continuously (Shu and Wei, 2007). Moreover, due to the greater amount of premixed combustion in new combustion concepts, that are being developed to comply with the increasingly restrictive emission standards without efficiency penalties, combustion noise will play a decisive role in such designs (Gatellier et al., 2006; Russell and Haworth, 1985; Rust and Pflueger, 2000). Additionally, while control of the overall engine noise is imperative to fulfill the current legislation, sound quality and comfort are essential to the customer's purchasing decision (Hirano et al., 1999; Lee et al., 2005, 2006; Payri et al., 2006). Thus, it is clear that there is a need to consider combustion noise together with other design factors, such as performance, emissions and driveability, from the earliest stages of engine development. When combustion takes place, a sudden pressure rise produces the well-known Diesel knock (Hickling et al., 1979). This pressure rise causes the vibration of the engine block, which in turn radiates aerial noise. The block vibration is caused both by pressure forces exerted directly by the gas and mechanical forces associated with piston slap, bearing clearances, elements deformation, and friction, which are powered by the pressure forces during combustion (Anderton, 1979; Cho et al., 2002; Ohta et al., 1987).

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Furthermore, pressure forces strongly depend on the combustion process, which is mainly dominated by the fuel burning velocity (Grover and Lalor, 1973). Since this velocity is controlled by the injection rate, current flexible injection systems permit the pressure forces to be controlled independent of any other engine operation parameter. According to these mechanisms, in-cylinder pressure characterizes the excitation source of the system (pressure and mechanical forces), while its response is associated with the vibration of the block wall. The final effect of this vibration is the noise radiation, which can be coupled with the noise from other sources. Attending to the basic processes discussed above, the problem of engine noise may be tackled as in any noise generation process. Thus, it may be assessed from the consideration of the excitation source, whose energy, through one of the various propagation patterns (the transmission path), reaches the emitter. This element emits sound pressure waves that spread through the air up to the receptor. According to these physical mechanisms, two possible approaches may be considered to assess combustion noise: determining the transmission path and the emitter characteristics or a direct correlation between the source and the radiated noise.

Due to the time-variant and non-linear features of the block response (Desantes et al., 2001; Villaroel and Ägren, 1997), the first approach is complex and requires a high computational effort (Ihlenburg, 2003; Steffens and Nussmann, 2006), so it is usually restricted to the structural design of the block and is only applied once for each engine family. However, the second approach is widely used because it is more suitable for integration at the early stages of engine development. This approach for combustion noise assessment was promoted by Austen and Priede, who in 1958 proposed the "block attenuation" method (Austen and Priede, 1958) in which a relation between the source and the receptor is established. According to this theory, the engine structure responds linearly, and thus its characteristic attenuation curve can be used to estimate the sound pressure level spectrum relative to the combustion noise emitted by the engine. As a result, this attenuation curve allows the overall engine noise level from in-cylinder pressure traces to be estimated under any engine operation conditions. However, some works (Desantes et al., 2001; Villaroel and Ägren, 1997) show that diverse patterns exist for acoustic energy propagation through the engine block and that its response is highly non-linear and time dependent. These features render the study of combustion noise through the block response notably complex. In this situation, the study of combustion noise should be attempted from the intuitive analysis of physical mechanisms in the noise source, which are directly extracted from the measurement of the incylinder pressure during engine operation. Difficulties relative to block vibration may thus be avoided by establishing direct correlations between those mechanisms and the noise level or the sound quality. Such correlations may allow for the qualitative evaluation of the sensitivity of combustion noise both to engine operating conditions and combustion strategies (Payri et al., 2009; Torregrosa et al., 2007).

In this paper, the application of such a procedure to noise level assessment in to be studied. Taking advantage of the methodologies defined in previous work (Torregrosa et al., 2007), a novel approach based on operation and combustion indicators highly correlated with radiated noise levels is presented in this paper. This work discusses a contribution in current requirements of suitable tools for combustion noise analysis in state-of-the-art diesel engines in transient operation. The noise level issues at steady engine operation are addressed to determine a suitable regression with convenient indicators and compared with the traditional approach. Mainly transient operation (Broatch et al., 2009) is studied, showing that the multiple regression approach proposed is also suitable to estimate the temporal evolution of engine radiated noise. Finally, a summary of the main conclusions is given.

2. Experimental Setup for Study

The experimental work has been done on a Euro IV direct injection turbocharged multi cylinder diesel engine. The engine was loaded by an E125LC eddy current dynamometer directly coupled to its clutch. The gear box case remained assembled with the block so that the vibration pattern of the engine structure was kept as close as possible to real-life operation. The test bench was placed inside an anechoic chamber whose cut-off frequency was 100 Hz. Noise measurements in free field conditions were possible in this chamber, since its volume is almost 100 times the volume of the bench and the distance between the engine and the chamber wedges was longer than 3.5 m. The dyno was physically and acoustically isolated from the engine by means of sound absorbing panels.

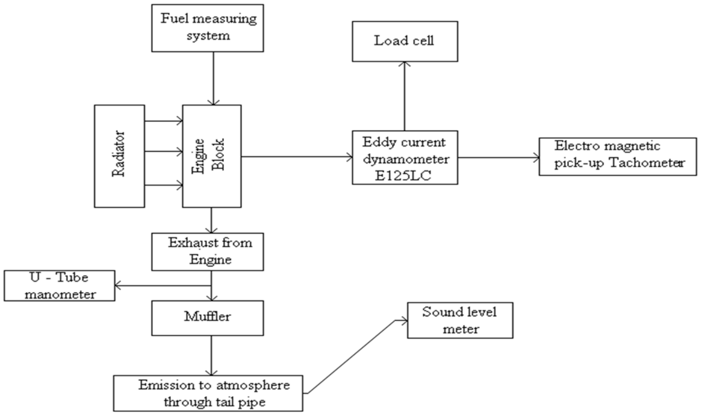

Figure 1. Scheme of the experimental setup used in the study.

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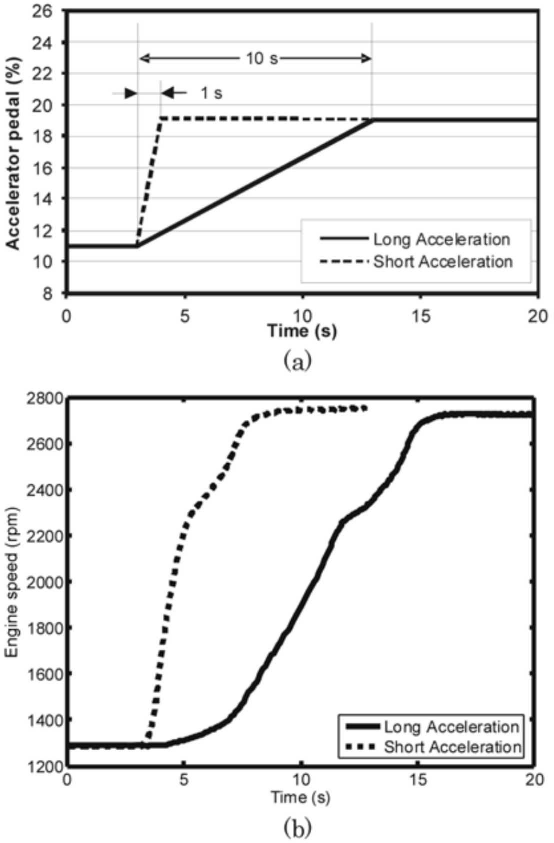
Figure 1 show the experimental layout used in this study. The diagram is self-explanatory. All noise data were taken on a relative basis in the closed base of the laboratory and in the presence of other engines and instruments in the close vicinity. The background noise was recorded before experimentation. In order to keep background noise to minimum, all other engines and machines in the laboratory were shut down during recording of the background noise. In order to carry out the related experiments precision sound level meter was used. The sound level meter was placed at an angle of 45^0 to the centre line of the tail pipe of the muffler at a distance of 1m from the tail pipe exit. The engine speed and torque were set to the appropriate values simultaneously.

Since an absolutely constant engine speed cannot be maintained, even at steady operation, the different engine cycles were distinguished by using the pulse signal generated by each crankshaft rotation with an optical encoder as a reference. This pulse signal has also been used to trigger the measurement systems so that synchronized signals were available for study. Furthermore, the pulse signal is crucial for measurements in the transient operating condition because the in-cylinder pressure signal must be synchronized with sound pressure records to avoid any time lag between the measured and the predicted temporal evolution of noise. Measurements at several speeds and torques were performed in this study to cover a wide range of steady engine running conditions. For each running condition – characterized by the speed and the torque – the engine noise was varied dramatically by changing the injection schemes and the injection parameters. For each injection scheme, the following parameters were varied:

- Rail pressure
- Injected fuel mass during pilots and main injection
- Injection timings (main start of injection and dwell angles)
- EGR (Exhaust Gas Recirculation) rate

In the case of transient tests, two constant load acceleration ramps were evaluated. From a steady condition at 1300 rpm, the engine was sped up over 2700 rpm while maintaining the torque 40 Nm. The electronic control of the dynamometer permitted torque variations lower than ±5% in all tests. In this study, two durations were considered:

- Short acceleration - acceleration time of 1 s
- Long acceleration - acceleration time of 10 s



(a)

(b)

Figure 2. Engine control during transient tests: (a) actuation laws of the accelerator pedal; (b) temporal evolution of the engine speed.

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3. Noise Level Evaluation under Steady Conditions

3.1. Classical Approach

The classical approach is frequently used by engine development engineers to assess the overall engine combustion noise level at steady operating conditions (Payri et al., 2006; Torregrosa et al., 2007). This approach, which was introduced by Austen and Priede (Austen and Priede, 1958), is based on the calculation of the 'structural attenuation' curve, which is the difference between the in cylinder pressure and the radiated noise 1/3-octave band spectra. In this theory, since a linear response of the engine structure is assumed, its characteristic attenuation curve can be used as a transfer function to estimate the sound pressure level spectrum of the engine noise from the in cylinder pressure trace.

The results obtained with the classical approach show that, even though a good correlation coefficient is obtained. This fact demonstrates the high dependence of block attenuation on engine type. On the other hand, the high mean and maximum errors obtained with the optimized curve could be due to the dependence of block attenuation on engine operating conditions.

3.2. Proposed Approach

To offer an alternative to the classical approach, a procedure based on the definition of indicators relative to engine operation that are characteristic of dominant noise sources is proposed. As a first approach, the procedure proposed in (Torregrosa et al., 2007) was considered. In this procedure, combustion components determined from the decomposition of the in-cylinder pressure into three sub-signals -- pseudo-motored, combustion and resonance (Payri et al., 2005) -- were proposed to assess the overall engine noise at steady operation conditions. Despite the high degree of accuracy of such a procedure, its application to transient running conditions was discarded, mainly due to the increased complexity that may be involved when determining the pseudo-motored sub-signal. In this study, only the spirit of such a method was followed, so that components representative of the noise sources were also explored.

Thus, several components relative to engine operation (speed, load, boost pressure, injection settings, etc.) that indirectly affect the combustion process were considered first. Combustion components that characterize the incylinder source (caused by combustion), such as maximum and mean pressure p, maximum first and second order pressure derivatives, and sound pressure level, were also explored. The value of each component was quantified by the average of the values estimated for all the cycles recorded in the four cylinders. The redundant components (variables with a correlation coefficient higher than 0.9) were grouped and the most representative one of each group was considered as a candidate.

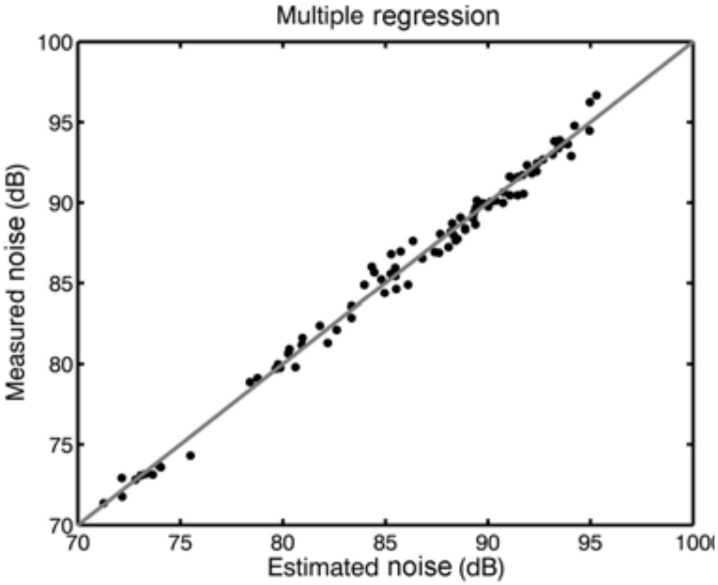

Figure 3. Noise level estimation with the multiple regression approach.

Figure 3 shows the comparison between the noise levels estimated with this multiple correlation equation with two indicators and the noise levels observed experimentally. A good collapse is observed and the agreement may also be regarded as very good. As a first approach, the obtained regression provides an adequate trade-off between calculation simplicity and accuracy.

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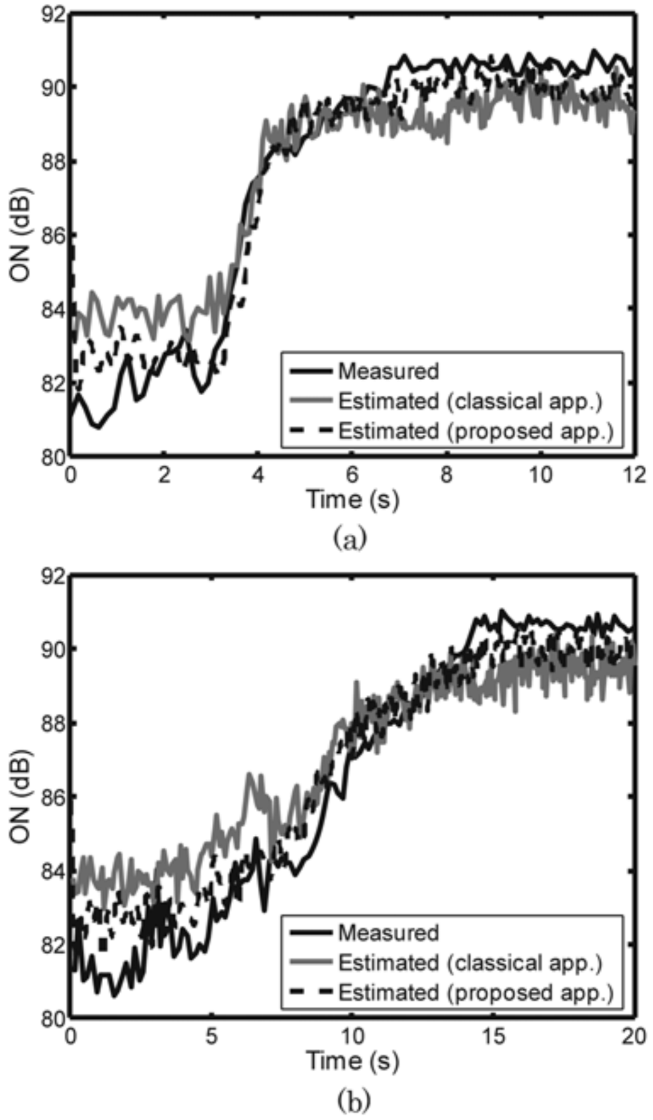
4. Noise Level Assessment in Transient Operation

In this section, the feasibility of the two methods described in the previous section for noise level assessment in transient operating conditions will be explored. With this purpose, the optimized block attenuation curve and the multiple regressions, obtained previously from noise analysis in stationary operation conditions, were adapted to the prediction of the overall level temporal evolution of the noise radiated by the engine in transient operation. In both cases, the pulse signal generated by each crankshaft turn of the optical encoder was used to isolate the in cylinder pressure traces of the four cylinders on a cycle-to cycle basis. Then, the four traces were added in the time domain in order to obtain the pressure evolution characteristic of the noise source during each cycle.

For noise estimation through the classical approach, the 1/3 octave band spectrum of this signal was calculated using traditional Fourier analysis. Subtracting the optimized attenuation curve from the in-cylinder pressure spectrum gives an estimate of the spectrum of the radiated noise during one cycle. Finally, overall noise was calculated from the estimated spectrum. Applying the same procedure to all the measured cycles, the temporal evolution of the overall noise could be predicted. For noise assessment by means of multiple regressions, the instantaneous engine speed was determined by recording the crank angle signal supplied by the optical encoder coupled to the crankshaft. The cycle-to-cycle isolated in cylinder pressure signals permit the calculation of four maximal pressure derivatives.



(a)

(b)

Figure 4. Sound pressure level at transient conditions. Comparison between measured and estimated evolution both with the classical and the proposed approaches:

(a) short acceleration; (b) long acceleration.

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Figure 4 shows the comparison between the predicted and measured engine noise level at each of the acceleration ramps considered in the study. The measurements (compare Figures 4 and 2b) evidence that engine noise is highly correlated with engine speed and that the produced noise variation (around 10 dB) was high enough to permit the evaluation of the potential of both approaches for noise assessment during transients. Other studies have also shown that engine speed is the operation parameter best correlated with the radiated noise level (Torregrosa et al., 2007). Furthermore, the rise in noise is also due to other engine operating parameters, such as injection pressure, timings and fuel mass, which are varied by the electronic control unit during the acceleration. The comparison of the measurements with the overall noise estimated with the two procedures leads to the following remarks:

- Even though the predicted noise level variation during the accelerations (6-9 dB) is lower than that observed in the measurements, the temporal evolution has been acceptably reproduced with the two procedures.
- The approach based on the classical attenuation curve overestimates the noise level before the acceleration, when the engine operates in the steady condition, and in the first part of the ramp. The agreement between prediction and measurement is good at the end of the ramps, but the model underestimates the sound pressure level after the acceleration, when the engine goes back to steady operation.

5. Conclusions

A novel approach to noise level assessment in DI diesel engines in transient operating conditions has been presented. From an innovative methodology based on the selection of operation parameters that indirectly affect the combustion process and combustion components that characterize the in-cylinder noise source, two significant indicators that allow for the prediction of the overall noise level have been identified. Engine speed was the operation parameter best correlated with noise, whereas the maximum in-cylinder pressure derivative was identified as the most relevant parameter for the combustion process. This study compare favourably with the classic method based on structural attenuation curves in both steady and transient operating conditions.

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