

Instrumentation, Acquisition and Data Processing Requirements for Accurate Combustion Noise Measurements

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ABSTRACT

The higher cylinder peak pressure and pressure rise rate of modern diesel and gasoline fueled engines tend to increase combustion noise while customers demand lower noise. The multiple degrees of freedom in engine control and calibration mean there is more scope to influence combustion noise but this must first be measured before it can be balanced with other attributes. An efficient means to realize this is to calculate combustion noise from the in-cylinder pressure measurements that are routinely acquired as part of the engine development process. This publication reviews the techniques required to ensure accurate and precise combustion noise measurements. First, the dynamic range must be maximized by using an analogue to digital converter with sufficient number of bits and selecting an appropriate range in the test equipment. Second, the encoder resolution (sampling rate) must be chosen in order to achieve the required frequency range and to avoid aliasing that is typical in event-based acquisition systems. Third, to calculate combustion noise the resulting cylinder pressure must be suitably chosen or windowed before applying an FFT and processed on a cycle-by-cycle basis. Each of these aspects is discussed including the errors that can be incurred with each step and how to minimize them. Recommendations are provided with an emphasis on a single setting that minimizes the errors across the wide range of speeds and loads encountered in engine dynamometer testing.

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INTRODUCTION

In-cylinder pressure measurements are commonplace in engine development and are used to calculate peak pressure, burn rates, IMEP, etc. The same signal can be used to calculate combustion noise. A measure of noise is highly desirable as it allows the engine development engineer to simultaneously optimize this attribute along with others such as fuel consumption, emissions, torque and exhaust temperature [1, 2]. The combustion noise calculation is outlined in Figure 1. The motivation for using combustion noise in place of maximum pressure rise rate is shown in Figure 2. It correlates better to engine radiated combustion noise (calculated from a 4-mic average of full load noise minus no load noise) and is also expressed in NVH units which makes assessments of levels and changes more useful to an NVH engineer. Unlike the traditional burn parameters, combustion noise is quite sensitive to data acquisition settings. The focus of this publication is to investigate the factors that minimize the errors in calculating combustion noise.

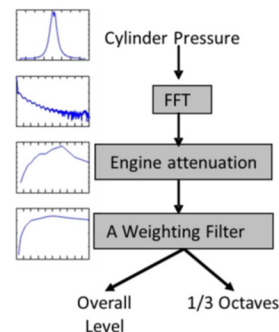


Figure 1. Combustion noise calculation

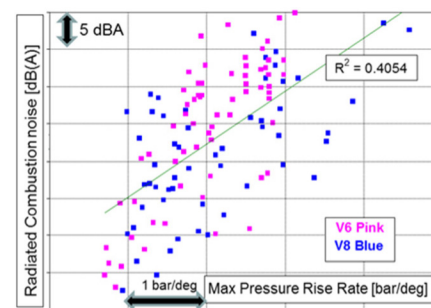


Figure 2. Correlation of maximum pressure rise rate and combustion noise to radiated noise for 12 PFI engines

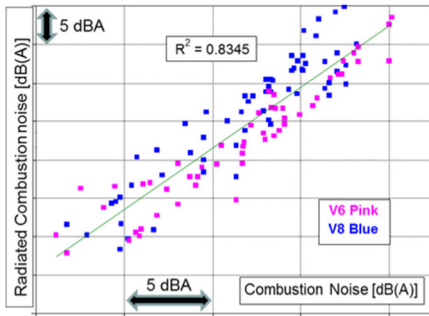


Figure 2. (cont.) Correlation of maximum pressure rise rate and combustion noise to radiated noise for 12 PFI engines

DYNAMIC RANGE

Until the recent advent of 16-bit systems, commercially available real-time combustion data acquisition systems had 14-bit analogue to digital converters (ADCs). Legacy equipment still in use in dynamometer labs may have 12-bit ADCs. For a given ADC, a dynamic range (DR) must be selected in the software. An experimental study was conducted to compare the difference in 12- and 14-bit systems versus a reference 16-bit system and to investigate the effect of the software dynamic range setting. The data acquisition equipment used is shown in [Table 1](#).

Table 1. Acquisition equipment for dynamic range study

Test 1	A&D CAS	12-bit
Test 2	A&D CAS	14-bit
Reference	LMS Test.Lab Scadas	16-bit

The engine used for the study was a V-8 turbo diesel. The engine was operated over a range of steady-state speed / load conditions and acquisition settings as shown in [Table 2](#). Two range settings were used: the first was optimal with 10% head-room, the second setting was a typical initial setup of 200 bar. The percent of the optimal is the second number shown in the dynamic range column. The test was conducted first with the 12-bit ADC and the reference system and second with the 14-bit ADC and the reference system. The CAS and LMS systems logged data simultaneously. The sample rate in the reference system was fixed at 100KHz with a 50KHz anti-aliasing filter. The sample rate in the combustion system is dictated by the encoder resolution and the engine speed. The encoder resolution was fixed at 0.2degrees (1800 pulses per revolution).

Table 2. Speed/load and dynamic range settings for diesel engine

Engine speed (rev/min)	Torque (% of max)	Dynamic range, % of optimal
Diesel		
650	Idle	90%, 15%
1500	0%	90%, 20%
1500	50%	90%, 28%
1500	100%	90%, 38%
2500	0%	90%, 20%
2500	50%	90%, 30%
2500	100%	90%, 40%

The cylinder pressure data from CAS and LMS was processed into combustion noise using the method described in [Figure 1](#) and compared to each other in [Table 3](#). As we are seeking to minimize measurement system errors so that real differences can be determined, a maximum error of 0.5dBA was chosen as the limit of acceptability. It can be seen from the results that the error in the 12-bit system at idle when using only 15% of the available dynamic range is unacceptable. Once the dynamic range gets to 20% or above at the 1500rpm points, there is no meaningful difference between bit count or dynamic range. A 14-bit ADC is always going to be preferred given the choice but in this case it does not have a difference at off-idle conditions. For diesel data then it can be recommended that at least 20% of the available dynamic range be used and the authors recommend 25% to provide some margin. For example, if an ADC is -5 to +5V volts, the range setting should be set such that at least 2.5V of that is used. In a typical diesel, the peak pressure of the engine is approximately 50 bar at idle going up to 150-200 bar at full load. The 25% of available range can usually be accomplished with one setting to cover all the ranges if that setting is chosen to be just above the maximum peak pressure i.e. the maximum peak pressure would fill the -5 to +5V range in the earlier example.

Table 3. Differences in combustion noise due to dynamic range versus the reference system

Engine speed (rev/min)	Torque (% of max)	Combustion noise: CAS minus reference system			
		12-bit 90% DR	12-bit standard DR	14-bit 90% DR	14-bit standard DR
650	Idle	0.5	1.1	0.4	0.6
1500	0%	0.1	0.1	0.1	0.1
1500	50%	0.1	0.1	0.1	0.1
1500	100%	0.1	0.2	0.2	0.2
2500	0%	0.0	0.1	0.0	0.0
2500	50%	-0.2	0.0	-0.3	0.0
2500	100%	0.2	0.1	0.2	0.1

If the frequency content of the cylinder pressure is of concern (rather than just a single number) then further consideration must be given to dynamic range at idle. [Figure 3](#) illustrates the benefit that arises from optimizing the range regardless of ADC bit count. The frequency spectra at the 1500 and 2500rpm points were line-on-line regardless of setup.

The study was repeated with an I-4 naturally aspirated gasoline engine with a 14-bit system only. The engine was operated over a range of steady-state speed / load conditions and acquisition settings as shown in [Table 4](#). Two range settings were used: the first was optimal with 10% head-room and a 12.5 KHz analogue filter, the second setting was a typical initial setup range of 100 bar with no analogue filter. The percent of the optimal for the 100 bar setting is the second number shown in the dynamic range column. The CAS and LMS systems logged data simultaneously. The encoder resolution was fixed at 0.5 degrees (720 pulses per revolution).

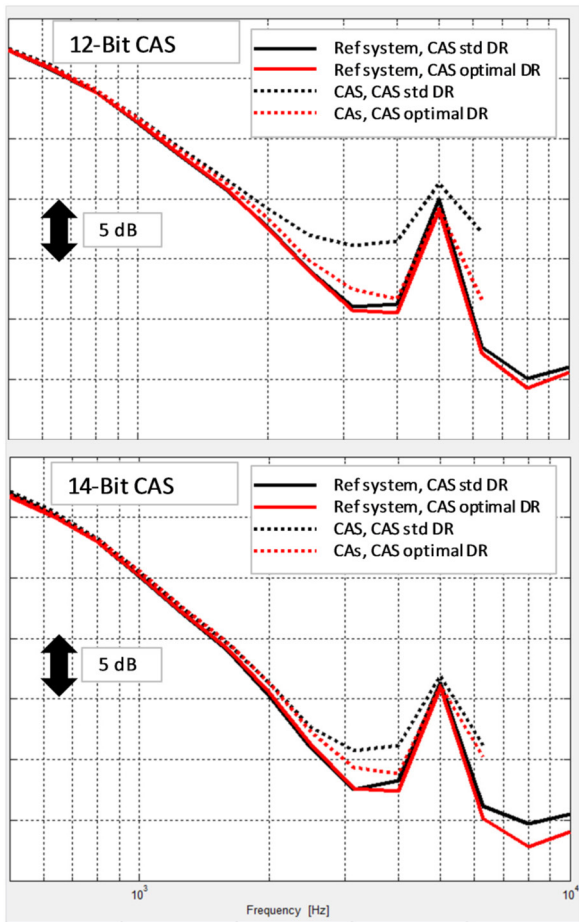


Figure 3. Comparisons of cylinder pressure spectra at diesel idle point

Table 4. Speed/load and dynamic range settings for gasoline engine

Engine speed (rev/min)	Torque (% of max)	Dynamic range, % of optimal
Gas		
750	Idle	90%, 15%
1500	0%	90%, 6%
1500	50%	90%, 22%
1500	100%	90%, 25%
2500	0%	90%, 8%
2500	50%	90%, 25%
2500	100%	90%, 39%
3000	0%	90%, 8%
3000	50%	90%, 25%
3000	100%	90%, 44%
4000	0%	90%, 8%
4000	50%	90%, 28%
4000	100%	90%, 42%
5000	0%	90%, 11%
5000	50%	90%, 33%
5000	100%	90%, 44%
6000	0%	90%, 11%
6000	50%	90%, 33%
6000	100%	90%, 50%

The cylinder pressure data from CAS and LMS was processed into combustion noise using the method described in Figure 1 and the results compared to each other in Figure 4. It can be seen that from 2000rpm and above at 50 and 100% load the error is below our 0.5dB threshold and at 2500rpm and higher almost zero regardless of the range setting used. At 1500rpm 50 and 100% load the effect of dynamic range becomes much more pronounced. The error incurred

even with optimal dynamic range is due to aliasing which will be discussed in the next section on Encoder Resolution. It can be seen that at 0% load the speed needs to be 4000rpm or higher to minimize the error. This is due to a combination of insufficient signal-noise ratio and the aliasing just referenced. A special mention needs to be made about idle combustion noise. It was found that the range must always be optimized for idle otherwise errors are introduced. Generally speaking, idle and light load combustion noise in conventional gasoline engines is not an issue and the errors shown here are of little real-world concern.

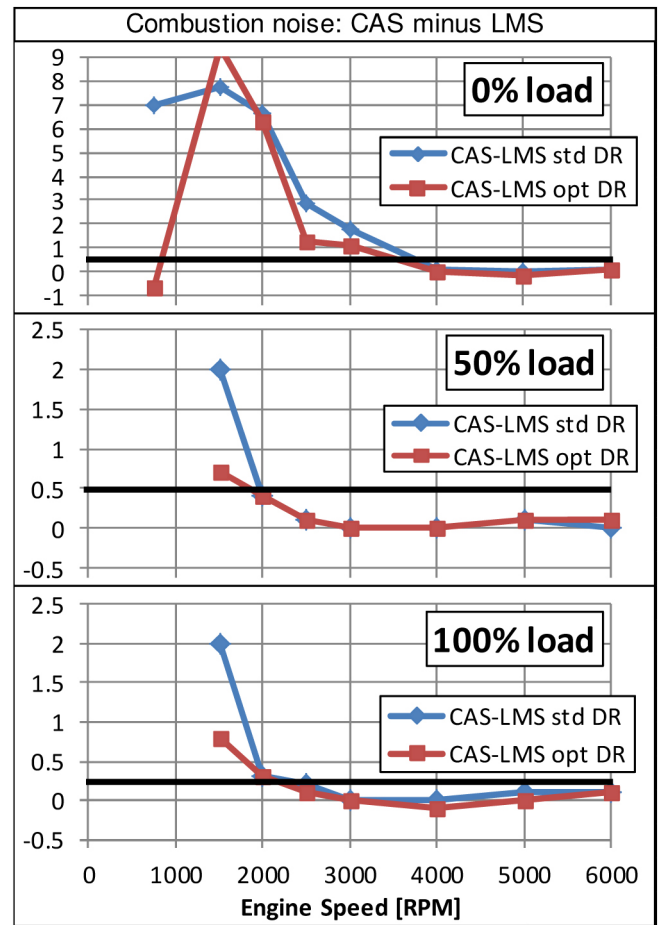


Figure 4. Combustion noise deltas for the diesel engine at different loads

ENCODER RESOLUTION

The first reason to select an encoder resolution finer than 1 degree is to ensure an appropriate frequency resolution for the combustion noise calculation. Combustion noise is generally considered to be in the 500-5000 Hz range although narrower ranges are also used. Table 5 shows the maximum frequency available with different resolutions at different engine speeds, calculated using the formulae:

$$F_s = \text{Engine speed (rev/min)} * 1/60 \text{ (min/sec)} * \text{encoder pulses/rev (deg/rev)}$$

$$F_n = F_s * 0.5$$

$$F_{\text{max}} = F_n * 0.8$$