A Review of Structural Attenuation in Combustion Engines

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Abstract: *The rate of pressure (which mainly depends on the ignition delay period) and quantities of combustion gas formed during this period are a key parameter to analyze combustion-based noise. A shorter delay period means lesser amount of combustible gas formed and hence lesser combustion noise. Hence, delay period must be reduced as much as possible for effective reduction of combustion noise. Structure and layout of engine also plays a significant role. There are many approaches to control combustion noise. One of these includes reducing cylinder pressure spectrum typically in middle and high frequency ranges. Other include reducing ignition delay period or number of combustible gases formed during this period. Increasing the stiffness of parts, use of turbo charging process and use of split injection methods have also proved to be other effective methods*.

Increase in the compression ratio and chamber temperature may shorten this delay period. However, an increase in compression ratio can cause a rise in noise due to slapping motion of skirt. Various parameters of fuel injection system like instance of fuel injection, injection pressure, number of nozzles and fuel supply rate also affect the combustion noise. Increasing the pressure of injection or engine speed leads to an increase in the amount of fuel accumulated during the delay period resulting in rise of combustion noise.

Keywords: *Engine structure, acoustics, noise control*

1. Introduction

A technique to quantify combustion-based noise has been proposed by [1]. The combustion-based noise was most dominant in frequency range of 800Hz- 4kHz [2]. Acoustic measurements of noise outside the engine may be used for combustion noise analysis only when the engine is operated in such a way that contribution of combustion events towards the noise emissions becomes predominant. This can be achieved either by either advancing injection timing or by changing Cetane number of fuel. Alkyl blended fuel were used to maximize in cylinder pressure so that combustion noise becomes dominant [1].

Structural attenuation of engine structure also plays a vital role in determination of combustion-based noise. Values of structure response functions was found to fall by about 10dBA in 500Hz - 5kHz frequency range [1]. More recently, AVL has developed a noise meter which is based on analysis of engine indicator diagram [3]. Good correlation was observed when data from this noise meter was compared with results obtained from computer programming. Figure no 1 shows structural response functions of a group of 9 engines as recorded by an AVL noise meter [1]. The response of direct injection high-speed diesel engines falls by 12dB over 5kHz frequency range [1]. Further Shu was able to predicted this transfer function by setting an explosive charge inside cylinder which was locked at fixed crank angle position as seen from figure no 2 [4]. Different functions for various designs of combustion chambers and different amounts of explosion charges have also been compared in his work.

All the methods discussed above use expensive and time-consuming methodologies to analyze the transfer function of combustion noise, consequently an alternative method of analysis has been analyzed which involves use of Cepstrum analysis.

Cepstrum analysis is an important method of signal processing which has wide applications in source separation [5]. Psychoacoustic analysis of noise emissions from a S.I. engine has been carried out using Cepstrum analysis [6]. This methodology has also proved effective for cylinder pressure reconstruction [43], fault detection in gears [7] and condition monitoring of engines [8].

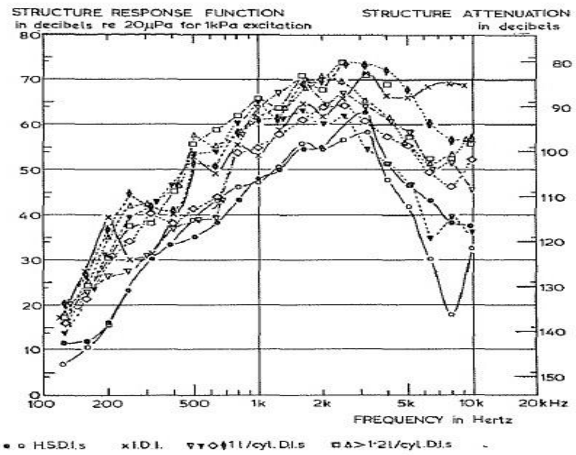

Fig. 1. AVL structural response function and structural attenuation

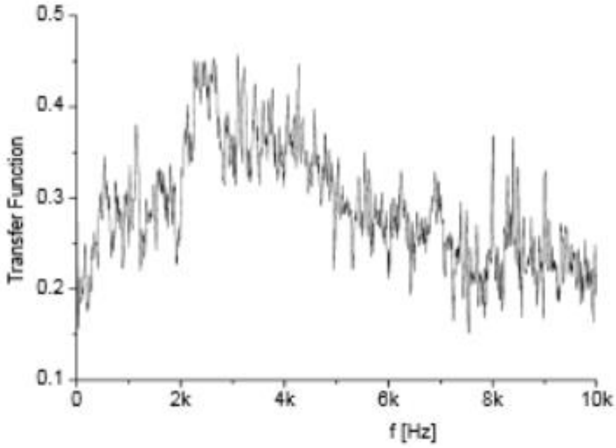

Fig. 2. Transfer function obtained by explosive charge

Mathematically Cepstrum can be defined as inverse spectrum of logarithmic power spectrum [9-20], i.e.

$$C_a(q) = |IFFT[\log[G_x(f)]|] \quad (1)$$

Where q is frequency in milliseconds & G_x denotes the Fourier transformation of function.
Since auto power spectrum density function is even, both its inverse Fourier transformations & Fourier transformations are equal. i.e.

$$C_x(q) = |FFT[\log [G_x(f)]]| = IFFT[\log [G_x(f)]] \quad (2)$$

As a noise source x(t) reaches a measuring point as an output signal y(t) after passing through a system represented by h(t), the information may be expressed by following equation:

$$y(t) = x(t).h(t) = \int x(\tau)h(t-\tau)dt \quad (3)$$

Taking Fourier transformation, we have:

$$G_y(f) = G_x(f) * G_h(f) \quad (4)$$

Further, taking logarithm and Fourier transformations on both sides this equation gets modified as:

$$\log(G_y(f)) = \log(G_x(f)) + \log(G_h(f)) \quad (5)$$

$$FFT[\log(G_y(f))] = F[FT\log(G_x(f))] + FFT[\log(G_h(f))] \quad (6)$$

Or

$$IFFT[\log(G_y(f))]=IFFT[\log(G_x(f))]+IFFT[\log(G_h(f))] \quad (7)$$

$$C_y(q) = C_x(q)+ C_h(q) \quad (8)$$

Structural response function for motored condition was evaluated taking noise emissions as output signal and in cylinder pressure as input. In case of firing conditions, the rate of heat release was taken as input parameter.

2. Experimental

Experiments were conducted on a KPKN2520 type, single cylinder diesel kirloskar rig having specifications as presented in table 1. Cases C was taken as reference base testing cases with fuel injected at 3600 RPM engine speed and 700 Bar injection pressure. 1mm^3/stroke of fuel was injected during pre -injection period as well as main injection period at crank angle positions 6° and 10° before top dead center positions of for this case.

Table 1: Engine specification

Type	Single cylinder DI 4 stroke diesel engine
Cooling	Air cooled
Rated power	3.75kW@1500RPM
Bore X Stroke	80mm X 110mm
Compression ratio	17.5:1

An AVL GU13P type piezoelectric transducer was used to acquire the instantaneous in-cylinder pressure data having various features enlisted in Table 2.

Table 2: Pressure transducer specifications

Range	0-200Bar
Sensitivity	15.8pC/Bar
Resonant frequency	130kHz

Various block vibrations were recorded by Endveco7240C make Mono axial accelerometers having features shown in table 3.

Table 3: Accelerometer transducer specifications

Range	0-1000g
Sensitivity	15.8pC/Bar
Resonant frequency	90kHz

A 4939 type Bruel and Kjaer free-field ¼″ make microphone having a preamplifier (type 2670) was used to acquire various noise emission signals. Main features of this transducer are shown in table 4.

Table 4: Microphone transducer specifications

Range	28-164dB
Sensitivity	4mV/Pa
Resonant frequency	4-100kHz

3. Results and discussions

Figures no 3-5 show the plots of this transfer function as obtained by Cepstrum analysis for various test case.

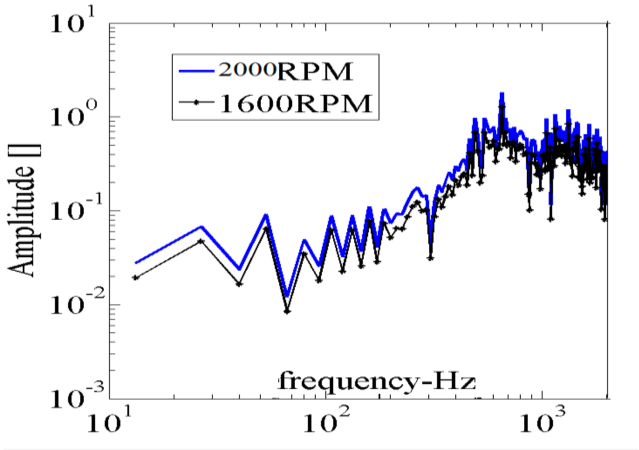

Fig. 3. Structural Attenuation Function (Motored)

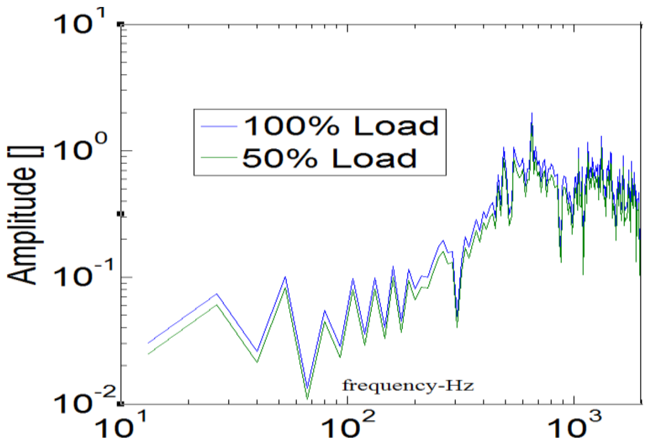

Fig. 4. Structural Attenuation Function (1600RPM)

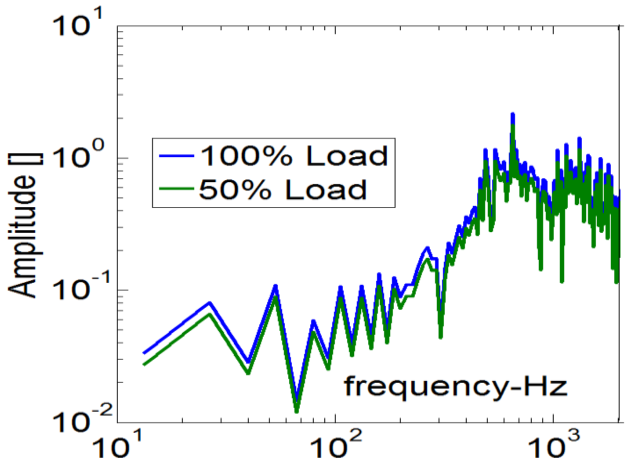

Fig. 5. Structural Attenuation Function (2000RPM)

It is clear from plots that noise transfer function for various cases showed same trends with higher values above 1kHz range. At low frequency ranges, various parts of engine have high rigidity and hence radiation efficiency is very low. In mid frequency ranges, longitude modes of vibrations in piston, connecting rod and crank shaft dominates which gradually increases the structural response of engine. In higher ranges, the radiation efficiency increases which may be attributed due to various Cast Iron parts. Several engines may use same materials for various parts; hence, various engines of different make having same size may show same variations in response function. The curves obtained by Cepstrum analysis show a significant difference in high frequency ranges above 1kHz. These variations may be attributed to differences in the designs of cylinder heads, engine block and cover, which also play a vital role.

Further neglected flow induced noise, the overall noise emissions (ON) from engine can be written as sum of direct combustion noise (CN) and motion-based noise (speed dependent), i.e.

$$ON = CN(H_1) + MN \tag{9}$$

Where H_1 is structural attenuation factor of combustion noise.
Assuming that mechanical noise levels (motored conditions) do not change significantly, the combustion noise levels for the given testing conditions were evaluated using transfer functions previously described as seen in figures no 6, 7.

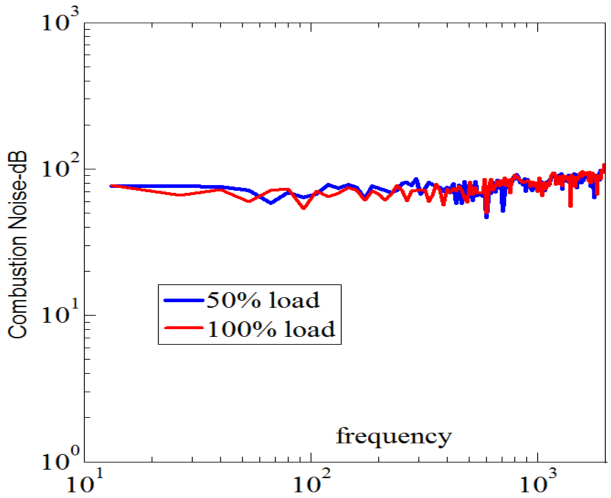

Fig. 6. Combustion noise -1600RPM

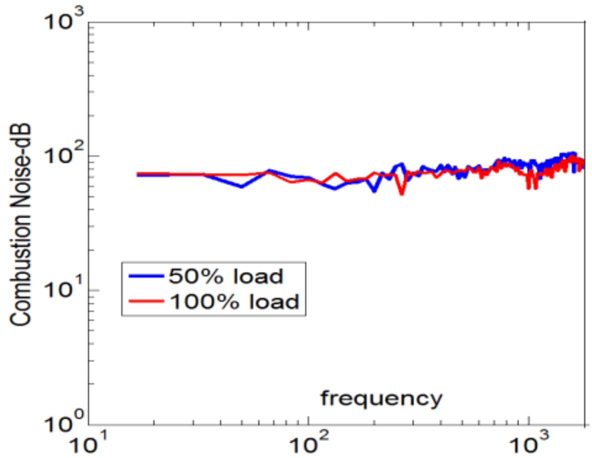

Fig. 7. Combustion noise -2000RPM

These plots are characterized by peaks in high frequency ranges which may be attributed to resonance of engine structure. Speed of engine showed no significant effects on the combustion noise levels, however increase of engine load caused a slight increase as the fuel was injected closer to TDC position and hence greater combustion noise emissions.

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