Role of Engine Design in Combustion Process

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Abstract: *Structural design of engines plays an important role in combustion based noise in engines. In this work the attenuation of engines has been overviewed.*

Keywords: *combustion process, combustion noise, structural design*

1. Introduction

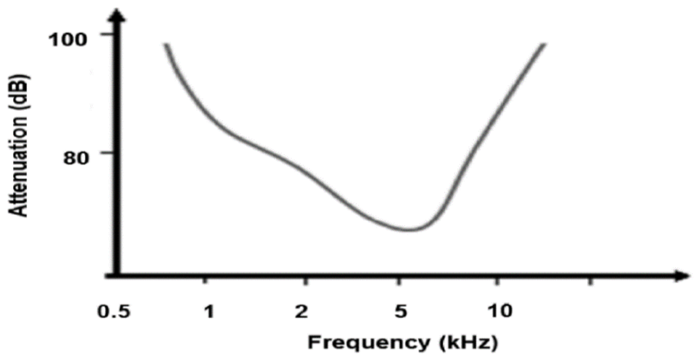

Fig. 1. Attenuation curve of engine[1-10]

This curve can be divided into three distinct regions:
a) Below 2000Hz-in this range the attenuation is very high as most of engine parts have high stiffness with their natural frequencies in low or mid ranges.
b) In mid frequency ranges of 2000Hz-5000Hz, the attenuation is small as most of natural frequencies of engine parts fall in this range.
c) Above 5000Hz- natural frequencies of most of the parts are above the natural frequencies of most of the parts, hence attenuation is quite high.

2. Background

Controlling the rate of pressure is the key to control combustion noise which mainly depends upon the ignition delay and quantities of combustion gas formed during delay period. A shorter delay period means lesser amount of combustible gas formed in the cylinder and hence lesser combustion noise. Hence delay period must be reduced as much as possible to reduce combustion noise. Structure and layout of engine also plays an important role.
Increase in compression ratio and chamber temperature also shortens the delay period. However increase in compression ratio may cause rise in the piston slap noise. Various parameters of fuel injection system like angle of fuel injection, injection pressure, number of nozzles and fuel supply rate also affect the combustion noise in engines. An increase in the injector pressure leads to an increase in the amount of fuel accumulated in the ignition delay period and hence an increase in the combustion noise.
If other factors remain unchanged, an increase in engine speed increases the fuel injection rate and hence greater quantity of fuel is injected in the period of combustion delay which leads to an increase in combustion noise.
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 amount of combustible gases formed during this period. Increasing the stiffness of

parts, use of turbo charging process and use of split injection methods in engine cycle have also approved to be effective methods [11-20].

3. Factors affecting

The analysis of in cylinder pressure is one of the most common way to examine the combustion noise in diesel engines. Anderton and Priede were first to observe that abrupt combustion led to high frequency contents of in cylinder pressure spectrum [14].Crocker suggested that frequency contents up to 300 Hz were related to maximum cylinder pressure [15]. Between 300Hz-2000Hz they were related to first derivative of in cylinder pressure, whereas above 2000Hz were related to second derivative of cylinder pressure.
Previous works have shown a relationship between peak of combustion noise and overall heat release rate[16].Rusell has developed a technique based on block attenuation curve which is still most reliable one for study of combustion noise[17].It was observed that higher slopes of rate of heat release curves led to higher combustion noise irrespective of fuel injection timings[18].There is a tradeoff between combustion efficiency and noise generated due to combustion[19].Efficient combustion leads to higher heat release rate near top dead center which gives rise to high frequency components in noise spectrum. Late heat release rates leads to lower in cylinder pressures and hence low frequencies in combustion noise.

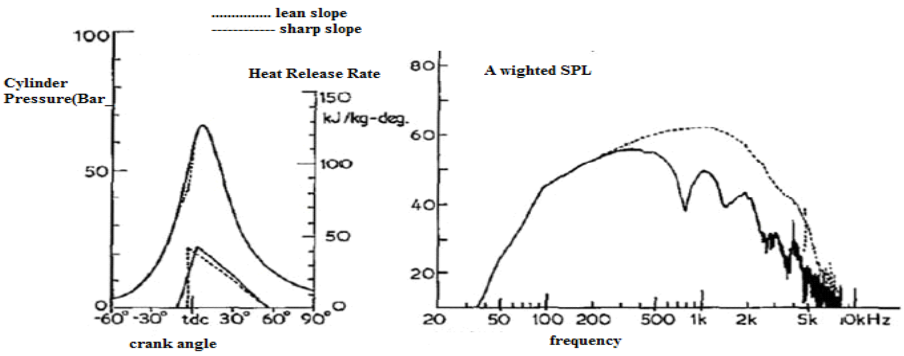

Fig. 2. Effects of heat release rate on combustion noise

It was observed that a 10dB reduction in sound pressure levels was possible without change in fuel consumption. However, there is a fall in efficiency of cycle and smoke emissions increase if ROHR is not terminated 50° BTDC [17].Combustion process in diesel engines vary with cycle which leads to variations in combustion noise [10].These variations may be attributed due to different fuel injection rates, compression ratios as well as difference in fuel spray process, mixture formation and flame propagation. Torregrosa has studied cyclic variations in combustion noise as given by figure no 2[11]. Variations may be attributed to resonance phenomenon occurring in combustion chamber.

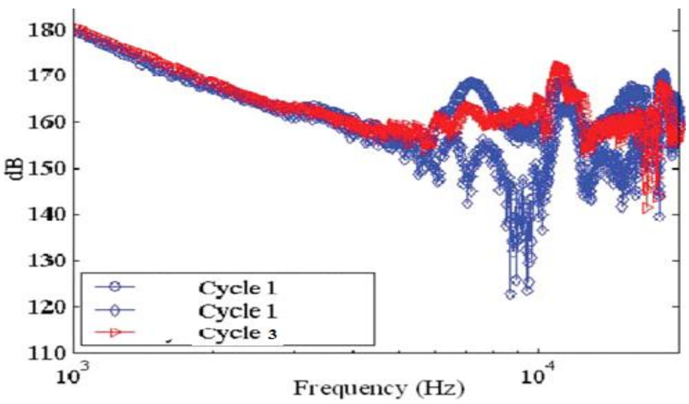

Fig. 3. Cyclic variations in combustion noise

4. Resonance phenomenon

Resonance process taking place in the combustion chamber effects the noise radiated from engines. Grover has observed high peaks in noise spectrum which may be attributed to this phenomenon [12].
Previous works have shown effects of gas temperature and effects of resonant frequency on high amplitude combustion chamber oscillations [13]. Hickling has observed several peaks in cylinder pressure spectrum by filtering data with cutoff frequencies in range 20Hz- 1500Hz which increase in amplitude with increase of load [14]. The frequencies of these peaks varied inversely with cylinder bore diameter. The resonant frequency (f_r) may be defined in terms of cylinder bore(B),axial length(L) and speed of sound(C) as:

$$fr=\sqrt{(\frac{K}{2L})^2+(\frac{q_{m,n}}{B})^2} \quad (1)$$

Where m,m,k determine circumfencial, axial and radial modes.

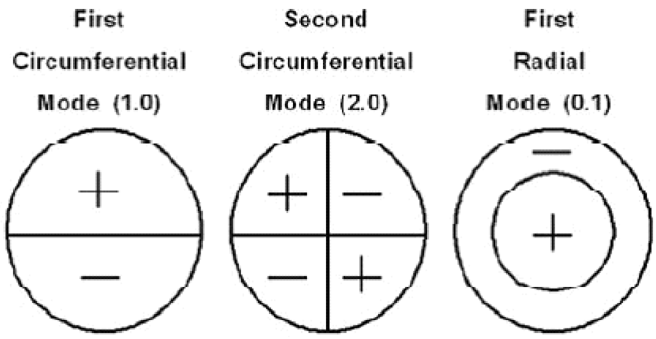

Fig. 4. Various modes of combustion chamber cavity

5. In cylinder pressure decomposition method

The signal processing methodology to decompose cylinder pressure signals was first proposed by Payri [15].In this methodology the cylinder pressure signals were decomposed into three parts namely-Combustion pressure, resonance pressure and compression pressure. The combustion art which is strongly dependent on rate of heat release is defined by injection strategy in engines. Using suitable cutoff frequencies motored part of pressure signal was isolated from excessive pressure signals. Figure no 4.78 shows results of such a methodology adopted for a cylinder pressure signal.

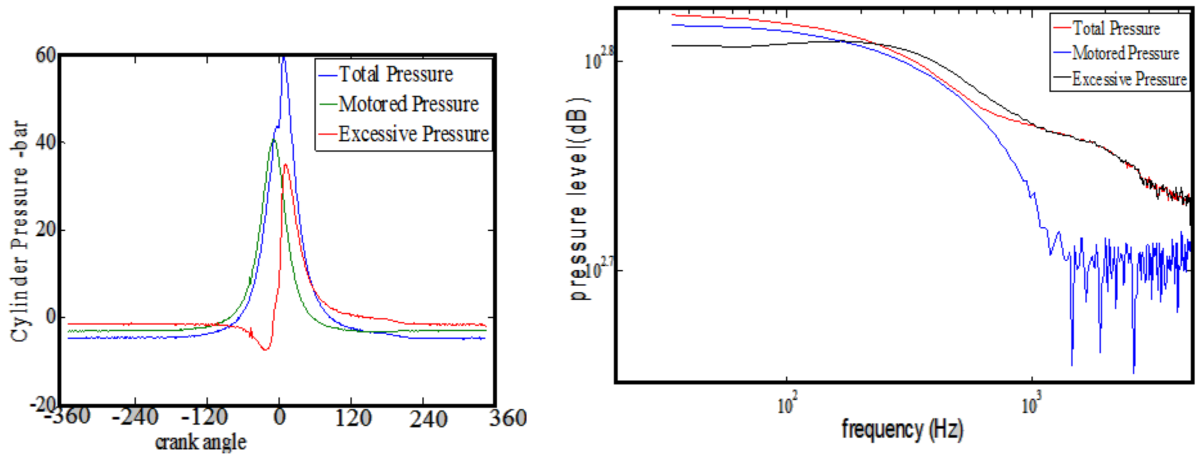

Fig. 5. Time and frequency decomposition of Cylinder pressure signal

As evident from these figures, motored pressure signal dominates the pressure spectra at low frequency ranges. By subtracting the motored pressure signal from total pressure signal, the excessive part of signal can be obtained. The resulting signal has contributions due to both resonance as well as combustion pressures. Resonance portion is clearly visible with fluctuating peaks in pressure spectra. Hence it can be isolated by filtering excessive pressure signal using high pass filter. The resulting resonance signal can be subtracted from excessive portion to obtain contribution due to combustion process. Figure no 4 shows total decomposition of cylinder pressure signal. It is evident from the lot that contribution due to combustion portion dominates in mid frequency range whereas the resonance phenomenon dominates at high frequency ranges [16].

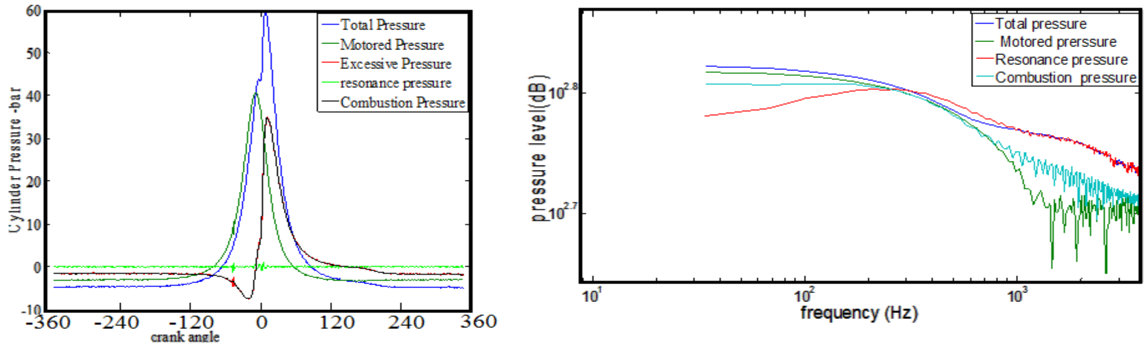

Fig. 6. Total decomposition of Cylinder pressure signal

The decomposed signals can be used to calculate noise indices defined in terms of ideal engine speed as:

$$I_n = n\log[\frac{N}{N_{ideal}}] \tag{2}$$

$$I_1=[\frac{N}{N_{ideal}}]\ [\frac{(\frac{dp}{dt})_{pilot}+(\frac{dp}{dt})_{main}}{(\frac{dp}{dt})_{motored}}] \tag{3}$$

$$I_2= 10\log(10^6 \int (\frac{{P_{residual}}^2}{{P_{motored}}^2})dt \tag{4}$$

Where $(\frac{dP}{dt})_{pilot}$ is maximum pressure gradient during pilot injection period , $(\frac{dP}{dt})_{main}$ is maximum pressure gradient during main injection, $P_{residual}$ is residual pressure and $(\frac{dP}{dt})_{motored}$ is maximum pressure gradient in motored pressure signal.

These indices can be further used to find overall noise (ON) emitted from engine as:

$$ON= C_0+C_1I_1+C_2I_2+C_nI_n \tag{5}$$

Where constants C_0,C_1,C_2 and C_n depend upon size of engine

6. Mathematical Model of Generation of Combustion Noise

In wavelet transformation complex morlet wavelet can be used as mother wavelet. A morlet wavelet may be defined in terms of central frequency f_c and bandwidth f_b as:

$$\psi(t) = \frac{1}{\sqrt{\pi f_b}} e^{i2\pi f_c t}\ e^{\frac{-t^2}{f_b}} \tag{6}$$

Figure no 6 shows real and imaginary parts of such a morlet wavelet having f_b = 1.5 and f_c = 1

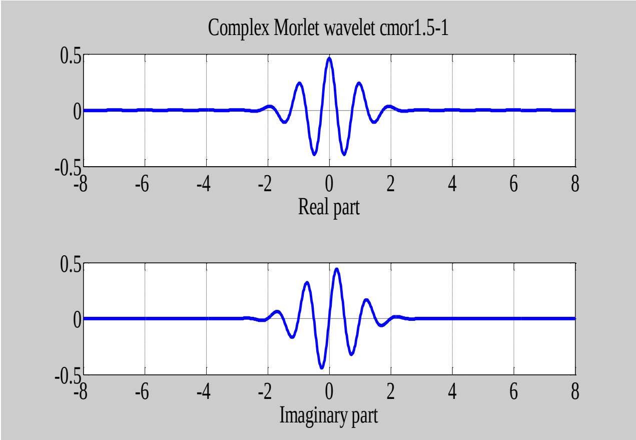

Fig. 7. Complex Morlet Wavelet

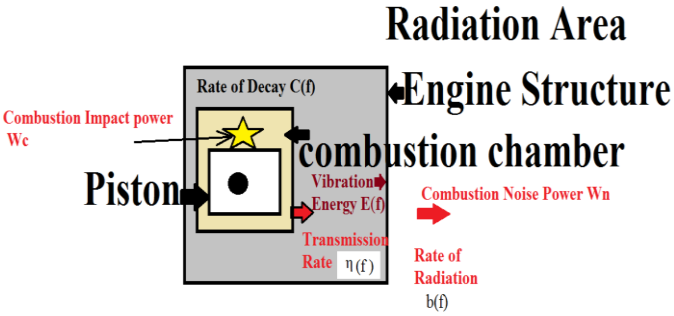

Fig. 8. Noise Generation Model

Figure no 7 shows a transient model of combustion noise generation in engines. This model can be analyzed by following three processes: generation of vibrational energy in combustion chamber due to combustion process, decay of energy in the engine structure and finally radiation of energy around engine surface.
The combustion process in engine generates combustion impact power (Wc) which can be expressed in terms of in cylinder pressure (p), impedance of medium (ρc) and cylinder surface area (A) as:

$$\text{Wc} = \frac{P^2}{\rho c} A \tag{7}$$

The available energy at engine surface can be expressed in terms of transmission rate coefficient η(f) as:

$$\text{E(f)} = \eta(\text{f})\int_0^t W_c dt \tag{8}$$

Differentiating both sides of this equation we have:

$$\frac{d}{dt}\big(E(f)\big) = \eta(\text{f})W_c \tag{9}$$

Taking into account the decay rate this equation gets modified as:

$$\frac{d}{dt}(E(f)) = \eta(\text{f})W_c \text{ -C(f)E(f)} \tag{10}$$

Where the decay constant C(f) may be defined as :

$$\text{C(f)} = -\frac{d[\log(Wn))]}{dt} \tag{11}$$

$$\frac{d}{dt}(W_n) = \text{b(f)}\eta(\text{f})W_c \text{ -C(f) } W_n\text{(f)} \tag{12}$$

Figure no 4.85-4.89 shows the plots of combustion impact power plotted for tests enlisted in table no 4.1 using reference value of W_0 as 10^{-12} Watts.

As clear from these results, the impact power had higher value at lower frequencies over a long crank angle duration. There was a fall in value of impact power with delay in injection period of fuel.

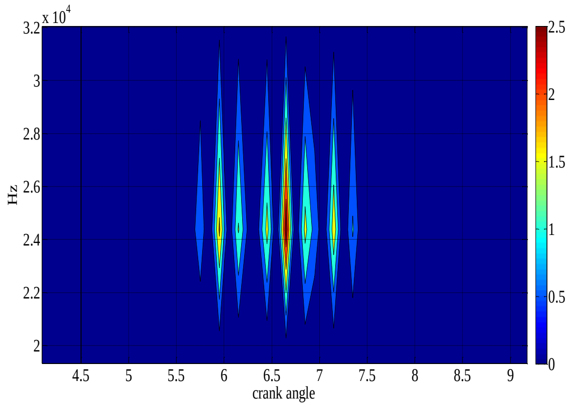

Fig. 9. Combustion Impact power (Case1)

7. Evaluation of Combustion Noise methods

A combustion noise measurement technique has been proposed by Lucas [7]. Austin & Priede have shown that combustion noise was most dominant in the frequency range 800Hz- 4kHz. 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 is maximum. This can be achieved without changing mechanical noise either by either operating the engine with advanced injection timing or by changing Cetane number of fuel used. Russell has used alkyl blended fuel to maximize in cylinder pressure so that combustion noise becomes dominant [7].
Structural attenuation of engine structure also plays a vital role in determination of combustion noise. Austin and Priede were able to determine this function by subtracting spectrum of in cylinder pressure level from the spectrum of noise emissions recorded at a distance of 0.9 m from engine structure [7]. Value of structure response functions fell by 10dBA in 500Hz to 5kHz range [7]. More recently AVL has developed a combustion noise meter which based on analysis of engine indicator diagram on frequency domain. Good correlation was observed when the data from this noise meter has been compared with that computed results from computer programming. Figure no 4.95 shows structural response functions of a group of 9 engines as recorded by AVL noise meter. The response of direct injection high speed diesel engines falls by 12dB over 5kHz frequency range [7].

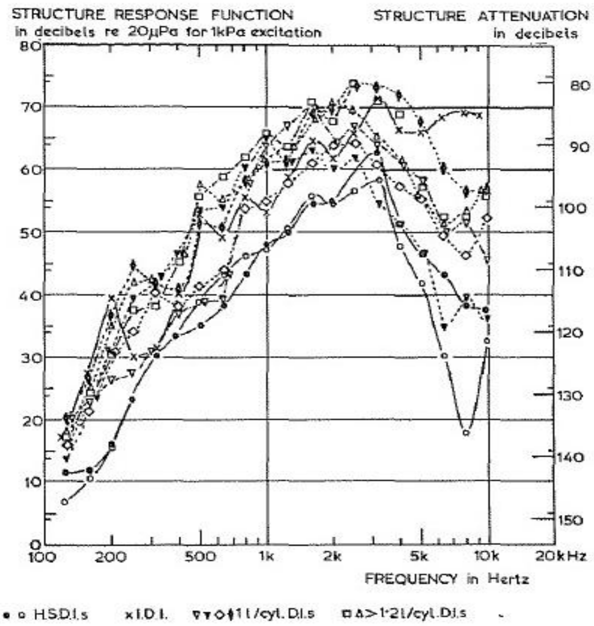

Fig. 10. AVL Structural response function and structural attenuation

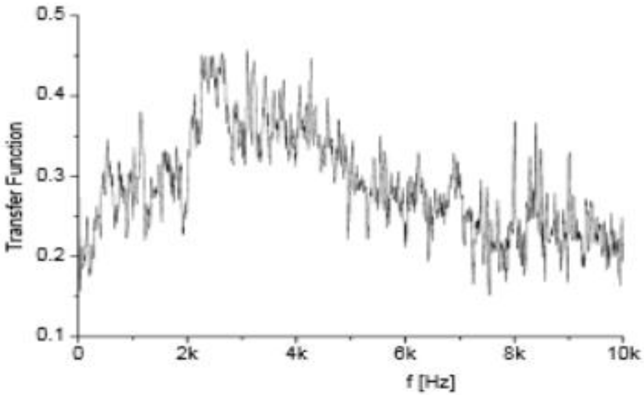

Fig. 11. Transfer function obtained by explosive charge

Shu has predicted this transfer function by setting an explosive charge in cylinder at a locked crank angle position as seen from figure no 11. Different functions for various designs of combustion chambers and different explosion charges were compared.
All the above discussed methods use expensive and time consuming methodology to analyze the transfer function of combustion noise, consequently an alternative method of analysis has been studied which evolves use of which include Cepstrum analysis.
The aim of this part is to provide an overview of combustion noise generation process. This was done by analyzing the methodology provided in previous works done. Engine combustion noise originates from combustion process taking place in cylinder. When fuel is injected inside the combustion chamber where high pressure air is present, then part of ignitable gas starts to burn causing a rapid rise in pressure as well as temperatures inside combustion chamber. The pressure wave thus generated also strikes the walls of combustion chamber causing resonance of structure. The vibrations are radiated in air through engine structure and are perceived as combustion noise.
In actual practice it is difficult to distinguish between combustion noise and piston slap as both coincide near top dead center positions. For sake of convenience it is assumed that combustion noise originates due to pressure vibrations inside engine cylinder and is transmitted to cylinder cover, piston, connecting rod, crank shaft and engine surroundings. Mechanical noise includes noise from piston-liner impact, valve operations, pump operations, injector operations as well as operation of various accessories and valve trains. Generally for indirect injection diesel engines and gasoline engines, the combustion process is less severe as compared with diesel engines; hence the combustion noise is lesser as compared with mechanical noise [20-24].

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