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A Review of Quantification of Noise in Engines

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Abstract: *During the decade of 1970's, introduction of more stringent noise control regulations led to more attention being paid towards the acoustic performance of engines. Priede analyzed a relationship between development of in cylinder pressure and subsequent noise emissions from engines. Kamal focused his work on finite element analysis of individual engine components for the dynamic analysis of engines. Later based on various noise transfer paths, main bearing of connecting rod was found to be a major transmission path for the indirect component of combustion based noise.*

Keywords: *Noise, vibro acoustic*

1. Introduction

In modern days, multidisciplinary approaches are being utilized for evaluation of NVH performance of engines. Some of these methods include modal analysis, finite element techniques (FEA), boundary element method (BEM), statistical energy analysis (SEA), lumped mass approach as well as transfer path analysis (TPA).

Each of these methods have specific frequency ranges over which they are most reliable e.g. FEA is more suited in low frequency ranges, whereas TPA is more suitable for medium frequency ranges. SEA gives results that are more accurate in higher ranges. Evaluation of acoustic performance of engines can be performed both objectively as well as subjectively using these techniques [1-6].

Figure no 1 shows plots of in cylinder pressure spectra for two different types of engines [7]. A difference of about 20dB is seen at 1KHz frequency.

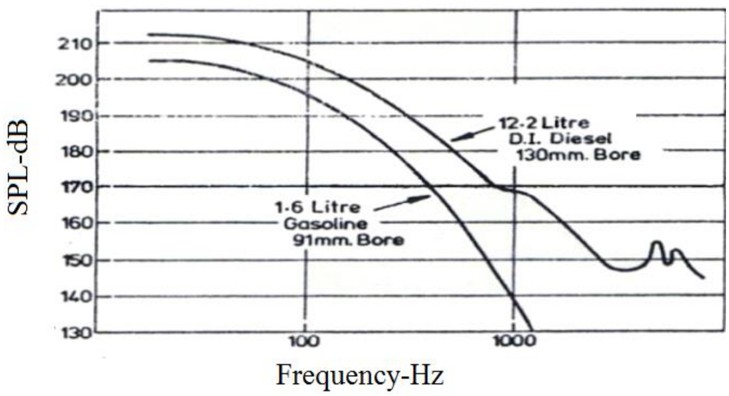

Fig. 1. In cylinder pressure spectrum

Based on various mathematical relationships, Anderton developed models to quantify the combustion-based noise according to type of engine [8]. It involves calculation of mechanical impedance Z(f) between the force applied at top of piston F(f) and average mean square root velocity v(f) of engine block. i.e.

$$Z(f) = \frac{\sqrt{V^2(f)}}{F(f)} \quad (1)$$

The average surface velocity V(f) may be expressed in terms of in cylinder pressure (p) and cylinder bore (B) as:

$$V(f) = \frac{p\pi B^2}{4Z(f)} \tag{2}$$

Further, the relationship of radiated acoustic power (W) from a surface may be written as:

$$W(f) = \rho CSV(f)\sigma = \frac{p^2}{\rho C} \tag{3}$$

Where σ is radiation efficiency and S is radiated surface area.
Combining the above relationships, we have:

$$W(f)=\sigma SC\rho\frac{p\pi B^2}{4Z(f)} \tag{4}$$

The intensity of radiated noise I(f) is given by:

$$I(f)=\sigma C\rho\frac{p\pi B^2}{4Z(f)} \tag{5}$$

In order to minimize the dependence of engine speed, various in cylinder pressure spectra were analyzed. Variations in these plots were observed like a straight line in frequency ranges 0.8KHz – 3KHz. The slope of pressure spectrum in this range was defined as combustion noise index (Ƶ) [2].

Using further analysis, it was shown that in cylinder pressure spectrum p(f) may be expressed as:

$$p^2(f) \sim (\frac{N}{f})^{Ƶ} \text{ Antilog(3N)} \tag{6}$$

Where N is engine RPM

From the above relationships, we have:

$$I(f)\,) \sim (\frac{N}{f})^{Ƶ} \text{ Antilog(3N) } \rho cS\sigma\frac{p\pi B^2}{4Z(f)} \tag{7}$$

Or

$$I(f)\,) \sim (\frac{N}{f})^{Ƶ} S\sigma\,\frac{B^4}{z(f)^2} \tag{8}$$

Overall Intensity I_O can be expressed by integration over a given frequency range [f_1,f_2] as:

$$I_O \sim SN^{Ƶ}B^4\int_{f_1}^{f_2}\frac{\sigma}{f^{Ƶ}Z(f)^2} \tag{9}$$

Various empirical relationships have been developed at ISVR, University of Southampton for prediction of noise in terms of sound pressure levels for different types of engines. Some of these include [29]:

$$SPL_{\text{N.A. Direct Injection Diesel engines}} = 30*\log(N +50*\log(B) +106 \tag{10}$$

$$SPL_{\text{Turbocharged Diesel engines}} = 40*\log(N+50*\log(B)-135 \tag{11}$$

$$SPL_{\text{Indirect injection Diesel engines}} = 43*\log(N +60*\log(B)-176 \tag{12}$$

$$SPL_{\text{Petrol engines}} = 50*\log(N +60*\log(B)-203 \tag{13}$$

As compared to diesel engines, a gasoline engine operates at higher operational speeds has smaller bore and smaller reciprocating mass. Consequently, such an engine has lower in cylinder pressure and hence lower sound pressure levels of radiated noise as seen from figure no 2.

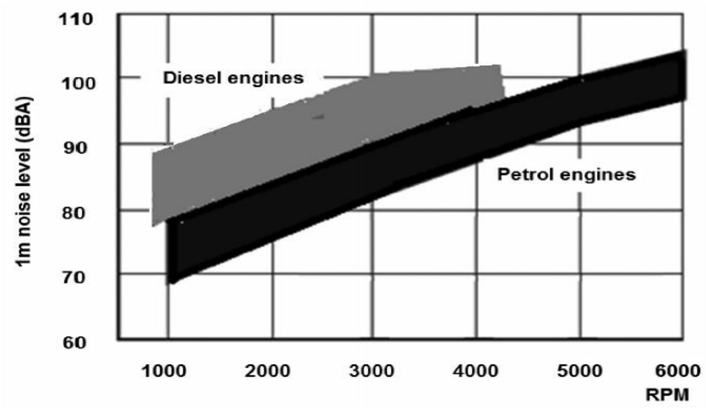

Fig. 2. Variations of sound pressure levels with engine speed

The diesel engine knocking refers to noise mainly in 500Hz-6000Hz range and is dominant under low speed idle operational conditions. Various moving parts in diesel engines are designed heavier and stronger as compared to gasoline engines in order to meet durability requirements under high operational pressures. Hence, the mechanical impacts in case of a diesel engine are stronger when compared to gasoline engines. There are additional sources of noise like turbochargers and operation of fuel injection pumps in case of a diesel engine. However, there are some sources of noise exclusively associated with operation of a gasoline engine. These include piston pin tickling noise under low speed conditions, clatter noise under cold operational conditions and slip stick piston noise originating from crankshaft [10-20].

2. Methods of quantification of noise

There are several techniques that have been used to identify various sources of noise in engines [3]. Some of these include selective shielding of parts, surface vibration method as well as acoustic intensity technique. Of these methods, the selective covering by lead is the most expensive as well as time consuming one. These techniques have been discussed further in the next part of this work.

a) **Selective lead covering method**-it is one of most reliable methods of source identification in field of engine acoustics. This method consists of measurement of noise emissions from engine using selective covering of engine parts with lead (which is a high transmission loss material). The increase in radiated noise is then noted by removing lead cover from the component. This procedure is repeated one by one for all major parts. Figure no 3 shows results of such a test that was performed on a 6 cylinder naturally aspirated diesel engine [3].

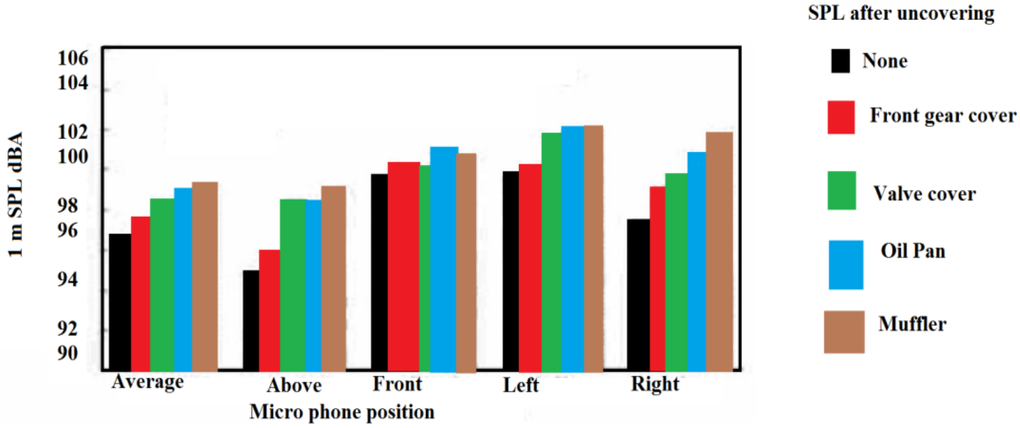

Fig. 3. Noise analysis using lead cover method

Total sound power level (SPL) emitted from this engine was found to be around 114dBA with valve cover, muffler, front gear cover and oil pan contributing about 21%, 10%, 8% and 7% respectively.

b) Surface vibration method-The A weighted sound power level of engine (L_w[A]) can be expressed in terms of acoustic impedance (ρc), surface velocity (u),radiation efficiency (σ)and surface area (S) by following relationship [3]:

$$L_w[A]= 10*\log(\rho c)+10*\log(S)+10*\log(\sigma)+10*\log(u) \quad (14)$$

The radiation efficiency is ability of surface vibrations to convert into air borne noise. The radiation efficiency can be estimated by considering engine as a radiating rigid sphere. This is also related to critical frequency of component, which may be defined as the frequency at which natural wavelengths of vibrations of given structure matches with those of radiated vibrations. At frequencies lower than the critical ones, the radiation efficiency is less than unity and vice versa.

The dominant range of critical frequency for components of a typical diesel engine lies in range 400-800Hz. The radiation efficiency rises at an approximate rate of 40d B/decade in ranges lesser than critical frequency. The value of critical frequency occurs when kr ≈ 4, where k is wave number and r is radius of an arbitrary sphere that has same volume as that of engine under consideration

Measurement of surface vibrations can be best done by mounting accelerometers on engine block. Positioning of accelerometers must be carefully done, as surface vibrations vary with wall thickness. Hence proper balancing between less and strong sensitive measurement points is necessary. The surface velocity can be calculated by using Fourier transformations (FT) to first convert acceleration data into frequency domain and then carrying out integration.

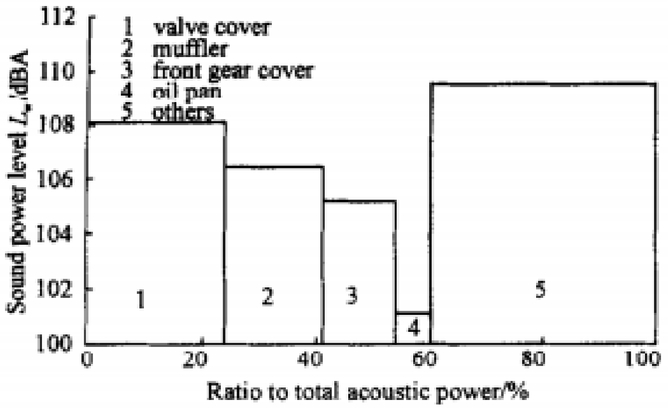

Fig. 4. Noise analysis using vibrational analysis method

Figure no 4 shows the results of contributions of various components as obtained by surface velocity method [6]. It can be seen that larger contributions occur from valve cover, muffler shell, gear cover and oil pan cover.

c) Use of Spectro- filters [3]

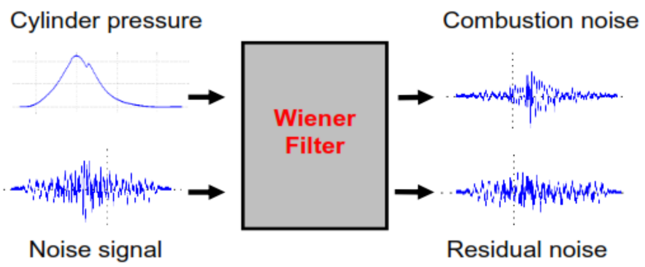

Fig. 5. Application of Wiener filter for estimation of combustion noise

Noise emissions from diesel engines has several contributing sources of which combustion based noise is a major one. Residual noise due to various other sources is shown in figure no 5. If the in cylinder pressure signal is known, these two sources can be separated using suitable Wiener Spectro-filters. These types of filters extract noise sources that are coherent with in cylinder pressure signals, hence providing an estimation of combustion based noise.
Wiener filter has a single input response P(t) giving a single output response C(t) as seen from figure no 6. The impulse response function has been denoted by H(t). The system is corrupted by external component M(t). This model can be represented by following relationships:

$$C(t)=P(t)*H(t) \tag{15}$$

$$G(t)=M(t)+C(t) \tag{16}$$

The Spectro-filter H(t) can be estimated from following equations:

$$W(f) = \frac{S_{PD}(f)}{S_{PP}(f)} \tag{17}$$

$$W(t)=IFFT[W(f)] \tag{18}$$

In these equations $S_{PP}(f)$ denotes the auto spectrum of P(t), whereas $S_{PD}(f)$ denotes the cross spectrum of P(t) and M(t). Convolution of input P(t) with W(t) gives an estimate of C(t) .i.e.

$$C^{\sim}(t)=P(t)*W(t) \tag{19}$$

$$G^{\sim}(t)=E(t)- C^{\sim}(t) \tag{20}$$

In case of a mono cylinder engine C(t) denotes the combustion noise, P(t) denotes in cylinder pressure developed, M(t) denotes the mechanical based noise, E(t) denotes total noise emissions and H(t) denotes the relationship function between in cylinder pressure and noise emissions as shown in figure no 6,7.

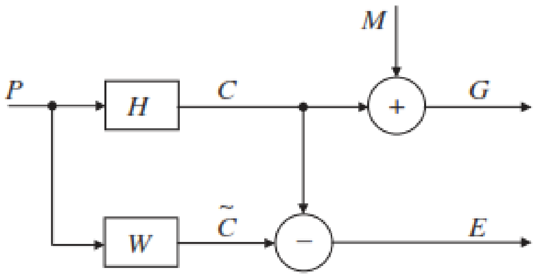

Fig. 6. Engine noise model (single cylinder)

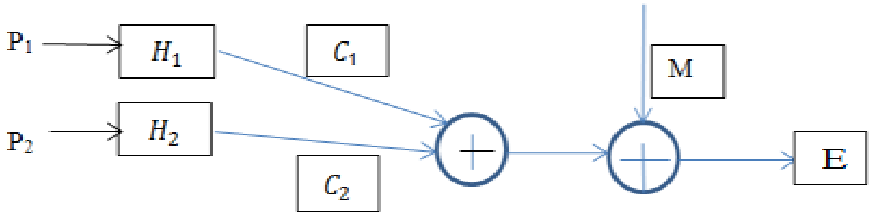

Fig. 7. Engine noise model (dual cylinder)

In case of a dual cylinder engine, figure no 7 shows the noise model. This is a multiple inputs and a single output (MISO) system. The combustion noise C(t) can now be considered as sum of the individual components produced by each cylinder i.e.

$$pC(t)=C_1(t)+C_2(t) \tag{21}$$

Various cyclo-stationary signals were used for calculation of Wiener filter as described above. These values were computed by subtraction of average values computed over a large number of cycles from original signals. The average values of signals have very reduced level in high frequency ranges (above 800Hz). As a result, the accuracy of Wiener filter is high in this range. Hence, these are well suited for analyzing noise emissions from a diesel engine as a major portion of energy of signals lies in this range.

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