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ANALYSIS OF VARIOUS NVH SOURCES OF A COMBUSTION ENGINE

ANALIZA RAZLIČITIH NVH IZVORA MOTORA S UNUTARNJIM IZGARANJEM

Amar Singh, Shubham Bharadwaj, Sunny Narayan

Subject review

Abstract: *The powertrain is the "heart" of a vehicle. It is the singular most expensive and most complex part of every vehicle. The powertrain consists of the engine, intake, and exhaust subsystems, and the transmission and drivetrain systems. The powertrain is one of the major sources of vehicle sounds and vibrations. In general, powertrain vibration and sound sources consist of the following: 1. Engine, including combustion-related sounds and vibrations, reciprocating unbalance, rotating unbalance, crankshaft torsional oscillations, etc; 2. Valve Train system, including valves, cam system, timing belt, or chain; 3. Accessories, including their unbalance and resonance; 4. Intake system and exhaust system vibrations; 5. Driveshaft first-order resonance; 6. Universal joint second-order bending vibrations and torsional vibrations; and 7. Axle vibrations due to gear tooth conjugation error, transmission error, pinion par eccentricity, slip-stick between pinion and ring gear, etc.In this work various sources of noise in an engine have been analyzed.*

Keywords: *engines; noise; vibrations*

Pregledni članak

Sažetak: *Pogonski sklop je 'srce' vozila. To je najskuplji i najsloženiji dio svakog vozila. Pogonski sklop sastoji se od motora, unosa i ispušnih podsustava te prijenosnih i pogonskih sustava. Pogonski sklop jedan je od glavnih izvora zvukova vozila i vibracija. Općenito, izvori vibracije i zvukova pogonskog sklopa sastoje se od sljedećeg: 1. motora, uključujući zvukove vezane uz izgaranje i vibracije, klipne neravnoteže, rotirajuće neravnoteže, torzijskih oscilacija koljenastog vratila…; 2. sustava razvodnog mehanizma, uključujući ventile, CAM sustav, razvodni remen ili lanac; 3. dodatnu opremu, uključujući i njezinu neravnotežu i rezonanciju; 4. vibracije usisnog sustava i ispušnog sustava; 5. rezonancija prvog reda vratila; 6. vibracija savijanja drugog reda kardanskog zgloba i torzijskih vibracija; i 7. vibracije osovine uslijed pogreške konjugacije zupčanika, pogreške u prijenosu, zupčanik prema ekscentričnosti, slip-stick gibanje između zupčanika i prstenastog zupčanika… U radu su analizirani različiti izvori buke u motoru.*

Ključne riječi: *motori, buka, vibracije*

1. INTRODUCTION

Engine vibrations can be classified as internal and external vibrations [1-3]. The internal vibrations are referred to as the vibrations of internal components of the engine, induced by the inertial force of moving parts and the variable pressure of combustion [4]. These vibrations usually must be suppressed to avoid engine malfunctions and damage/fracture and noise of parts. The frequently encountered vibrations are torsional and bending vibrations of the crankshaft, and vibration of the valves-camshaft system. The severe torsional and bending vibrations of the crankshaft could lead to fracture of the shaft and/or damage to the bearings [5]. Most of the internal vibrations result in noise, and are unlikely to cause dangerous stress of parts. The external vibrations are referred to as the vibrations of the entire engine system as a block, which is usually integrated with the transmission case. The external vibrations are due to unbalanced moment, inertial moment, or variable-output torsional torque. Engine vibrations are mainly due to the variable gas pressure in the cylinder, and the inertial force from the motion of the crank mechanism. Engine vibrations have detrimental effects on the internal parts, and can cause them to malfunction and thus have a reduced lifetime. Engine vibrations could also be transmitted to the engine's supportive base-like frames, or its accessories, and therefore lead to the vibrations of other systems [6-13]. Internal vibrations mainly lie in the torsional vibrations of crankshaft systems. The crankshaft has mass and elasticity; therefore, it constitutes a torsional vibration system. Under the excitation of the periodically modulated torsional torque, the crankshaft system is capable of making torsional vibrations. In operation, the crankshaft rotates and has an average torque applied to it. A static torsional deformation is associated with the crankshaft system.

Torsional vibration of the crankshaft system is a periodically varied torsional deformation superposed on the static deformation of the crankshaft. Torsional vibration always exists for an operational engine crankshaft. But it is not readily perceptible as the whole engine vibration [14]. The strength of the torsional vibrations can be estimated through measurement. If the frequency of the harmonic excitation torque coincides with the natural frequency of the crankshaft, the resonance occurs. If the resonance situation is severe, a disaster consequence such as crankshaft failure could occur. The external vibration is referred to as the block vibration of the entire engine system together with the transmission case, in which the bending resonance has been critical. In the engine crank system, the reciprocal motion of the piston system leads to reciprocal inertial force; the rotating crank generates centrifugal force. In multiple-cylinder engines, the cranks are arranged uniformly to attain uniform firing of each cylinder. The first and second inertial forces are usually balanced (except for the second inertial forces in a four-cylinder, four-stroke engine). The balance of the reciprocal inertial moment and centrifugal moment depend on the configuration of cranks. On the other hand, the output torque of the engine and the turnover moment applied on the entire engine are periodic due to the periodic variation of gas pressure and reciprocal inertial force.

These forces or torques result in vibrations of the complete engine block, which is usually treated as six-degree-of-freedom, including the up-down, front-rear, left-right, pitch, yaw, and roll. Thus, the isolation of whole engine block is necessary, and it will be discussed in a later section. The engine is usually mounted on the supportive base, such as the frame or sub frame of the vehicle, which is connected with the body.

In real applications, the engine undergoes various impact excitations and periodic excitations. The impact excitations are due to gap effects in moving parts such as bearings and piston-cylinders. The impact-induced response only lasts a short period of time and decays quickly due to damping dissipation. The main excitations leading to steady vibrations come from different force or torques, including the following: 1) Periodic tangential and radial forces acting on the crankshaft: these forces are from the gas pressure in the engine cylinder, the inertial and gravity forces from the piston, connecting rod, and crankshaft[15]. These forces are the primary sources of engine vibrations. 2) Excitation forces and torques due to rotating parts, such as the centrifugal force or torque caused by static or dynamic unbalance of the rotating parts. The engines of most road vehicles use a four-stroke process. An engine finishes a full working process with four steps (strokes): air intake, air compression, combustion (explosion or firing), and exhaust [16].

These steps are shown in Fig. 1. It takes a 180° rotation angle of the crank to complete one step of the process. As such, a full process takes a 720° rotation angle of the crank, i.e., two rotation cycles. Among the four steps, the combustion process produces force when compressed gas is combined and fired. Consider an ideal model of a single cylinder engine, in which a firing pulse appears every two cycles, or there is a "half" firing pulse for each cycle. The firing order, simply called order, is defined as the firing number in each cycle. Thus, the basic firing order for a single cylinder engine is the half order. For an engine with two cylinders, there is a half firing order for each cylinder in one cycle; i.e., there exists a whole firing order in one cycle for the two cylinders. Hence, the basic firing order for a two cylinder engine is 1st order. Similarly, there are two firing pulses, three firing pulses, and four firing pulses for a four-cylinder engine, six-cylinder engine, and eight-cylinder engine in one cycle, respectively [17]. Thus, their corresponding firing orders are 2nd order, 3rd order, and 4th order, respectively.

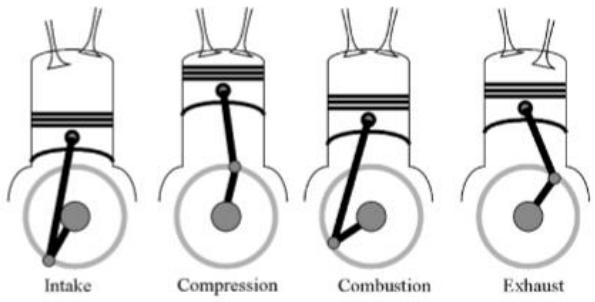

Figure 1. Engine Cycle

The typical noise sources of engines are schematically plotted in Fig. 2. The others such as engine block and injection pump are not indicated in the figure [18].

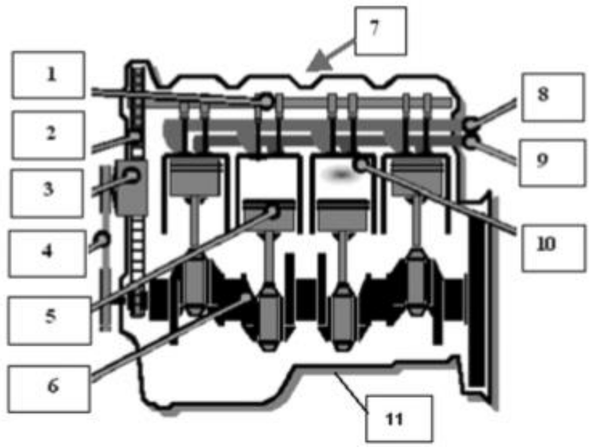

Figure 2. Engine noise sources

Fig. 2 Schematic of typical noise sources of an engine (1. valvetrain; 2. timing chain (or belt) noise (radiated from its cover); 3, 4. the noise from accessories such as oil pump, belt/ pulley, and fan system; 5. piston slap noise; 6. bearing noise; 7. structural noise of valve cover; 8. intake noise; 9. exhaust noise; 10. combustion noise; 11. oil pan (sump)).

Combustion noise intensity is proportional to the square of the pressure rise rate. The sound pressure level of noise is proportional to the logarithm of heat generation or release rate in the cylinder. Combustion noise is also dependent on ignition delay, speed, and torque load [19]. Mechanical noise mainly comes from the piston slap, the friction and impact response of the valve train, the meshing of gear and tooth belt, belt slippage, bearing operations, timing system and accessory systems, and oil pump systems. Mechanical noise is proportional to engine speed. The resonance of the engine block structure also radiates noise [20]. For the noise radiated from the engine surface, it is mainly from the radiation of the engine block surface and the bottom oil pan. The head of the cylinder and the cylinder cover also radiate noise. Aerodynamic noise includes the fan noise, intake, and exhaust noise. Fan noise is determined by speed, blade dimensions and configurations, and number of blades. The intake noise and exhaust noise are due to the pressure pulse, flow friction, and turbulence. The effect of tailpipe and surface radiation of silencer vibration are also primary sources of exhaust noise. The wide variations in engine design make it difficult to give a general ranking of engine noise in terms of sound pressure level [21]. As an example, Fig. 3 shows the contributions of variable sources to the total sound pressure level of noise (1 meter away from engine) of an engine. The noise contributors include: exhaust noise, intake noise, fan noise, combustion noise, piston slap noise, noise of accessories and belt, and valve system noise.

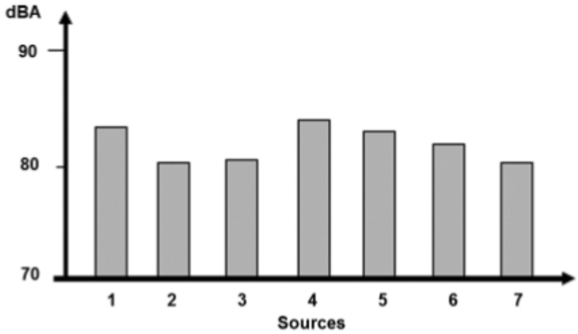

Figure 3. Contributions of varied sources to total sound pressure level of noise (1 meter away from engine) of an engine (1. exhaust noise; 2. intake noise; 3. fan noise; 4. combustion noise; 5. piston slap noise; 6. noise of accessories and belt; 7. valve system noise).

For various operational conditions, the contributions of the noise sources are quite different and are highly dependent on engine type. The specific frequency ranges of primary noise sources of a typical engine are illustrated in Table 1. The frequency ranges of the primary noise sources of an automotive engine are dependent not only on the engine and system structure, but also on operating speed and load. Therefore, the estimation and identification of specific frequencies must be determined through testing and analysis. By comparing the fundamental frequency and harmonics of these identified individual source noise with the spectrum of total noise, the contribution of individual noise source to total noise can be determined [22].

Table 1. Frequency ranges of noise sources

Source	Frequency ranges-Hz	Factor effecting
Combustion noise	500-8000	In cylinder pressure
Piston slap	2300-8000	Skirt-liner gap
Valve noise	500-2000	Acceleration ,valve seat gap
Cooling fan	200-2000	Engine speed
Intake	50-5000	Engine speed
Exhaust	50-5000	Engine speed
Injection	2000	Pump type
Gear	4000	Number of tooth
Accessory	3000	Alignment

Table 2 shows the decomposition of radiated noise from a V-6 engine. The testing of automotive engine noise is usually conducted in a semi anechoic chamber according to SAE-J1074. The room constant should be larger than four times the measurement surface [23]. In measurement, to avoid the disturbance of vibration and exhaust noise, the engine is installed together with a dynamometer on a base isolated from the rest of the floor; the exhaust tail pipe is connected with a pipe toward the outside of the test room. The background noise of the test room should be at least 3 dBA lower than the noise to be measured. The testing of the total engine noise needs to take into account the overall testing conditions. The steady test conditions should cover real operating conditions. In ramp-up testing from idle, the speed increase rate should be smaller than 15 rpm/s [24].

Table 2. Noise sources

Parts	dBA
Block	78
Head	76
Crank case	79
Intake manifold	78.9
Base	77.3
Cam cover	78.3
Front cover	77.97
Exhaust manifold	74.5
Oil pan	73.7

2. COMBUSTION NOISE

Engine combustion noise originates from the combustion in the cylinder. When fuel is injected into the engine cylinder chamber where high-pressure air exists, gasoline spark-ignites the mixed gas, and then part of the ignitable gas start to burn. The pressure and temperature increase rapidly. Then the combustion propagates from the firing part to other areas, and is associated with a continuous increase of temperature and pressure in the cylinder, with the combustible gas experiencing a circular flow motion. The pressure wave in the cylinder impacts the wall of the combustion chamber, which results in the structural resonance of the chamber. The cylinder parts usually have high stiffness and their natural frequencies are very high [25]. The frequencies of radiated noise are accordingly in the high frequency range. The pressure within the cylinder also exhibits periodic variation, which results in low-frequency vibrations of the cylinder. The combustion of mixed gas results in gas pressure changes, which results in structural vibration of the engine. The vibration radiates to the air through the engine surface and is perceived as combustion noise. In practice, it is difficult to distinguish combustion noise from mechanical noise. For convenience, we assume that the combustion noise is the noise due to combustion, originating from the pressure vibration within the cylinder and piston, transmitted to the cylinder cover, piston, connecting rod, crankshaft, and engine block, to the surroundings. We assume that the mechanical noise includes noise from mechanical interaction, impact and friction in piston-cylinder impact, timing gear or belt, valvetrain, injection mechanism, accessories, and belt. Generally, in a direct-injection diesel engine, combustion noise is higher than mechanical noise; in a non-direct-injection diesel engine, mechanical noise is higher than combustion noise; in low-speed operation, combustion noise is always higher than mechanical noise. The gasoline engine has less severe combustion; both its combustion noise and mechanical noise are lower than that of a diesel engine [26].

The generation of combustion noise has been attributed to the rapid change of cylinder pressure in the combustion process. The effect of combustion consists of the dynamic load due to rapid pressure change and the high-frequency gas vibration and impulsive wave [27]. The strength of the noise from the gas dynamic load depends on the rate of pressure rise and the timing of the maximum pressure rise rate [28]. If pressure remains constant, the noise cannot be generated. The variation of cylinder pressure is characterized by the rate of pressure rise, dp/dt. In terms of experiment, the noise strength of combustion noise varies with cylinder pressure, i.e.

$$I \approx [p_{\max}(\frac{\mathrm{d}p}{\mathrm{d}t})_{\max}]^2 \quad (1)$$

I is the sound intensity of the combustion noise, $p_{\max}$ is the maximum pressure or pressure peak in the cylinder, and $(\mathrm{d}p/\mathrm{d}t)_{\max}$ is the maximum rate of pressure rise.

The pressure in the cylinder of a diesel engine is larger than that of a gasoline engine, and the maximum rate of pressure rise is much higher than that of a gasoline engine; therefore, the combustion noise of a diesel engine is much higher than that of a gasoline engine. For a diesel engine, the direct-injection type has the highest cylinder pressure and the pressure increase rate, therefore it has higher noise. For a direct-injection engine, combustion noise is closely related to the combustion process [29]. The combustion process of a diesel engine consists of four phases: retarded combustion, rapid combustion, slow combustion, and late combustion. In the retarded combustion phase, the variation of pressure and temperature in the cylinder are small, and their effects on combustion noise are small. However, the retarded phase has a significant effect on the combustion process; therefore, it has indirect and significant effect on combustion noise [30]. In rapid combustion, the cylinder pressure increases rapidly, and it directly affects engine noise and vibrations. Combustion noise is generated mainly in the phase of rapid combustion. When cylinder pressure increases severely, cylinder parts experience a sudden dynamic load with a certain strength, the effect of which equals a slapping excitation. The engine is an intricate mechanical vibration system, for which different parts have different natural frequencies, and most fall in the high frequency range. Therefore, combustion noises radiated to the air through the transmission of engine parts are in the middle and high frequency ranges, which happen to be the most sensitive range of human hearing capability. A slow combustion phase also has an effect on engine high-frequency vibrations and noise. A late combustion phase has a small effect on combustion noise [31]. Normally, combustion noise of gasoline engines accounts for a small part of their total noise; however, when combustion-related knock occurs, cylinder pressure increases rapidly and leads to high-frequency knocking noise [32].The high-frequency vibrations of gas in the retarded combustion phase of a diesel engine, the firing and propagation of fuel result in the rapid pressure rise in the local district, and it also leads to the propagation of impulsive pressure waves. These impulsive waves reflect multiple times after they reach the wall of the cylinder. This process forms the high-frequency vibration of gas. It lasts quite a period of time in the expansion process.

The frequency of high-frequency vibration of gas in the cylinder can be estimated from sound velocity c and engine bore d as

$$f \approx \frac{c}{2d}. \quad (2)$$

3. SPECTRUM CHARACTERISTICS OF CYLINDER PRESSURE

The spectrum plot of cylinder pressure can be derived from the graph of cylinder pressure versus time. Cylinder pressure can be measured using a pressure sensor mounted on a cylinder head and connecting the sensor with the inside of the combustion chamber [33]. A minor change in the pressure curve has no significant effect on engine power, but it does have a significant effect on noise. An engine's power is determined by the averaged pressure curve from multiple cycles, whereas combustion noise is dependent on the actual curve reflecting transient pressure variation in each cycle [34]. The cylinder pressure curve usually is a variation of cylinder gas pressure with respect to time. To understand the frequency signature of cylinder pressure, the spectrum of cylinder pressure has been used. Fig. 4a plots the pressure of cylinder gas and the spectrum of a typical engine. As shown in Fig. 4b, the pressure spectrum is a function of gas pressure, the shape integration of the pressure curve, rate of pressure rise, and the second-order rate of pressure rise [35]. The spectrum of cylinder pressure can be classified within three regions [36]:

I. Low-frequency region: in this region, the maximum of cylinder pressure level is mainly determined by integration of the pressure curve and the value of pressure peak. The higher the maximum pressure of the cylinder, the higher the peak in the low-frequency range in spectrum curves.
II. Middle region of the spectrum has the feature that the pressure level decreases linearly in a logarithmic law; the slope depends on the rise rate of cylinder pressure $\mathrm{d}p/\mathrm{d}\varphi$. It is a function of the thermal release quantity at the beginning of combustion. The larger the $\mathrm{d}p/\mathrm{d}\varphi$ the more flat the straight-line portion, whereas the smaller the $\mathrm{d}p/\mathrm{d}\varphi$, the steeper the straight-line portion. The maximum rate of pressure rise plays an important role.
III. Third region exhibits a peak of pressure level. This is due to the rapid elevation of the pressure of the cylinder in the local district at the beginning of combustion, which results in the high-frequency

vibrations of gas and is related to second derivative of in-cylinder pressure.

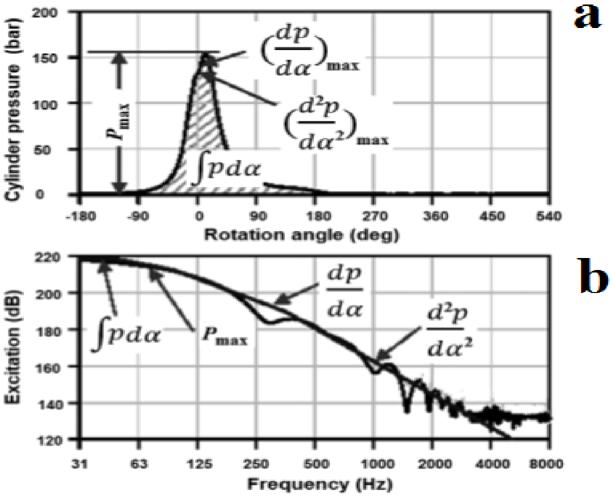

Figure 4. In-cylinder pressure analysis

The spectrum of cylinder pressure of some engines exhibits a line spectrum at a low-frequency range, which has several peaks at specific frequencies [37]. These specific frequencies are the firing frequency and their harmonics. In intermediate and high frequency ranges, the spectrum is continuous due to the rapid elevation of cylinder pressure in an impulsive way. The shape of the spectrum curve of cylinder pressure at a low frequency range is not affected by engine speed, except that the curve shifts toward high frequency when the rotating speed increases. This is because when the rotating speed varies, the pressure curve shape remains unchanged with respect to crank rotating angle. The high-frequency vibration of gas is mainly dependent on the size of the combustion chamber and the propagation speed of the impulsive wave. The frequencies corresponding to the pressure peaks in the third region of the curve are almost independent of engine speed [38,39]. From the spectrum of cylinder pressure, we learn that cylinder pressure is essentially the sum of a series of harmonics with different frequencies and amplitudes. Based on the superposition principle, the quantity of the cylinder equals the sum of the individual effects of the respective harmonics; therefore, the excitations of combustion gas to the cylinder can be considered as the sum of the individual excitations of this series of harmonics. The excitation of harmonics can be transmitted from the inside of the cylinder to the engine surface through three major paths, which results in surface vibrations and radiates noise. The first path goes through the piston, connecting rod, crankshaft, and main bearing, through which the vibration transmits to the surface of the engine block.

The second path goes through the cylinder head to the cover. The third path is the transmission from the sidewall of the cylinder to the outside of the cylinder and block. Many experiments demonstrate that most vibration energy from combustion is transmitted from the larger ends of the connecting rod and main bearing to the structure of the engine, and results in the surface vibration of the engine and radiated noise. The magnitude of combustion noise is not only dependent on the spectrum of the cylinder pressure, but also on the structural response and damping property of the engine. This is because noise is due to vibrations, and the vibrations depend on the properties of excitation and the structural response of the vibration system. The difference of pressure level between the inside of the cylinder and the outside of the engine is characterized by a decay, which is an attenuation quantity reflecting the inherent characteristics of engine structures. The decay is a constant value for a specific engine. Fig. 5 is the typical structural attenuation property of an engine [40]. It is independent of the property of excitations and the spectrum of the cylinder gas pressure. The engine's operating parameters such as speed, load, and the adjustment of the fuel supply system have no substantial effects on this property.

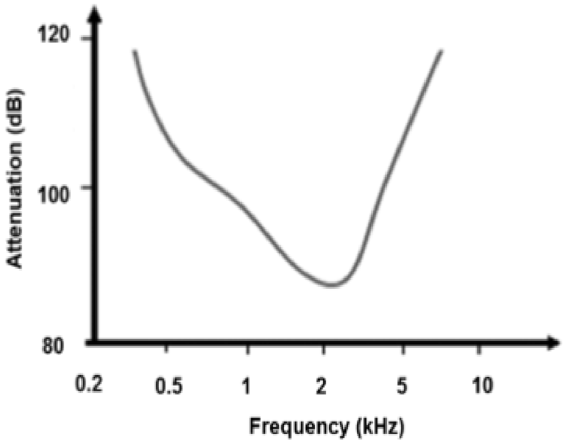

Figure 5. Engine structural attenuation

The structural attenuation curve could be divided into three regions [41]:

1. Below 1000 Hz, the attenuation is quite high. This is because most of the structural parts of the engine have relatively larger stiffness, and their natural frequencies are at the middle and high frequency ranges. Therefore, vibration response in the low frequency range is relatively small due to a larger structural decay, despite the fact that the excitation of pressure is larger.
2. In the middle frequency range from 1000 to 4000 Hz, the structural attenuation is small. This is because most of the parts' natural frequencies fall in this frequency range, which gives rise to a low attenuation property.
3. Above 4000 Hz, structural attenuation is very high. This high frequency range is above the natural frequencies of most parts; therefore, the structural attenuation is quite high. The engine's structure is an attenuator to combustion noise. The attenuation is larger at both low and high frequency ranges. The sound pressure level of the engine is high in the range of 800 to 4000 Hz, which corresponds to the range of low structural decay of the engine. In the low frequency range (below 800 Hz), despite the fact that cylinder pressure level is high, the noise radiated by the engine is low due to the engine's high structural attenuation.

In the high frequency range (above 4000 Hz), the structural attenuation is high and the cylinder pressure is small, while the noise sound pressure level is low. In this range, cylinder pressure level decreases with increasing frequency, and structural attenuation increases with increasing frequency. Therefore, noise decreases rapidly with increase in frequency. In the middle frequency range (800 to 4000 Hz), cylinder pressure is not as high as that in the low frequency range, but the structural decay is at a minimum in this frequency range. Therefore, the structural response is strong, and the sound level pressure attains its peak in this range. From the above observations we learn that combustion noise can be suppressed by reducing cylinder pressure through combustion optimization and by increasing structural decay of the engine structure. The rate of pressure rise is a fundamental factor controlling combustion noise; it mainly depends on the retarded spark timing and the quantities of mixture formation of combustible gas formed during the delay. A shorter retarded spark timing means that if the initial point of fuel injection is the same, and if the starting point of combustion is relatively earlier, the injected fuel quantity before the combustion is relatively smaller; therefore, the amount of combustible gas formed before firing is less, and the pressure increase after the firing is slow. Conversely, the longer the period of ignition delay, the greater the quantity of the combustible gas formed before firing. The fuel could combust simultaneously in the second phase of the combustion process, which results in a higher rate of pressure increase and higher maximum combustion pressure, and accordingly leads to higher combustion noise [42]. Therefore, in the design of the combustion system, the retarded combustion usually should be reduced as much as possible from the standpoint of noise control. For a specific engine structure, many factors affect retarded combustion. In normal operating conditions, compression temperature and pressure are the major factors influencing retarded combustion [43]. The advance angle of fuel injection and the features of combustion also have significant influence. The influence of the structure of the combustion chamber and operating parameters on combustion noise is due to their influence on retarded spark timing through compression temperature and pressure [44].

a. The structure and layout of the combustion chamber and the entire combustion system design have obvious influence on the rate of pressure increase, maximum combustion pressure, and spectrum of cylinder pressure.
b. Temperature and pressure: when compression temperature and pressure are increased, the physical and chemical preparation process of the fuel spark will be improved; the retarded spark is also reduced. The final temperature of compression mainly depends on the compression ratio, and also on the cooling water temperature, piston temperature, cylinder head temperature, and intake temperature [45]. The increase of compression ratio allows the gas temperature in retarded combustion to increase, and the final temperature and pressure at the end of compression to increase. This, accordingly, reduces retarded combustion, the rate of pressure increase, and the combustible fuel quantity accumulated in the period of retarded combustion, which also reduces the maximum value of thermal release rate and combustion noise. But the increase in compression ratio results in the increase of cylinder pressure, which leads to the increase of piston impact noise; therefore, it will not lead to significant reduction of total engine noise [46]. The compression increase results in a higher intake temperature and accordingly reduces the combustion noise of the direct injection diesel. The higher the intake temperature and the later the fuel injection, the higher the gas temperature and the shorter the retarded spark timing. The higher the load and the higher the temperature of the cooling liquid, the higher the temperature of the cylinder, and the shorter the retarded spark timing.
c. Fuel injection parameters: the parameters of the fuel system, including advance angle of fuel injection, injection pressure, number of injection nozzles, and the fuel supply law all influence the combustion process. If the other conditions remain the same, the increase of injection pressure results in the increase of injection rate and the increase of fuel quantity in combustion delay. The high-pressure injection improves the mixture of fuel and air, and increases the rate of combustible fuel generation [47]. This leads to the increase of combustible fuel accumulated in the period of ignition delay, and therefore increases combustion noise. Under the condition that the other parameters are unchanged for the injection system, the reduction of the injection fuel area results in an increase in the resistance of the fuel injection hole and reduces the rate of fuel injection, while reducing the quantity of fuel injection in combustion delay and reducing the noise of the direct-injection diesel.
d. Engine speed: if the other conditions remain unchanged, the increase of speed reduces the fuel injection time, and increases the fuel injection speed and the fuel quantity injected in the period of combustion delay. The increase of speed also increases the maximum cylinder pressure, the maximum of the rate of pressure increase, and the combustion noise. But usually the effect of engine speed on combustion noise is not extremely significant.
e. Load: for the indirect-injection diesel and gasoline engine, as their pressure increase is relatively smooth, when the load varies, the maximum combustion pressure change is relatively small and remains at a small value, and the impact on the cylinder from the piston is small [48]. The sound pressure level of noise under a full load could be smaller than that under the no-load case by a couple of decibels. With the increase of load, the thermal release quantity will increase; the combustion pressure peak and the rate of pressure rise will also increase. This results in a higher noise level. On the other hand, with the increase of load, the temperature of the combustion chamber will increase; the gap between the cylinder and piston will be reduced, which could suppress noise.

Overall, the load has a small effect on engine noise. The basic approaches to reduce combustion noise: in principle, the combustion noise can be reduced in the following two aspects. The first one is from its root cause, which includes reducing the spectrum of the cylinder pressure, particularly the magnitude in the middle or high frequency range; to reduce the period of ignition delay or reduce the quantity of mixed gas in the combustion delay [49].

The second approach is from the noise transmitting path: to increase the attenuation of the engine structure, particularly in the middle and high frequency range. The approach includes increasing the stiffness of the engine block and cylinder, and employing vibration isolation and sound insulation; reducing the gaps between parts such as piston and cylinder, cranks, and connecting rod; increasing the thickness of the oil film; using cylinders with smaller diameters; using greater numbers of cylinders or using a design with a larger ratio of stroke to cylinder diameter, to enable the output power to be less varied; or changing materials of the plate or shell parts (e.g., oil pan) by adding damping treatment. In general, combustion noise control requires trade-offs between the thermal efficiency and emissions. Several approaches used to reduce engine combustion noise include:

1. Piston with thermal insulation: the application of pistons with thermal insulation can increase the temperature of the cylinder wall, reduce the period of ignition delay, and reduce combustion noise of the direct injection diesel.
2. Injection delay: generally, the earlier the injection time, the larger the combustion noise. If the injection time is postponed, the combustion noise can be reduced. This is because the compression temperature and pressure in the cylinder varies with crank angles. The injection time affects the firing delay (combustion delay) through the compression temperature and pressure. If the injection time is set earlier, then the temperature and pressure are lower when fuel enters the chamber. Then the period of firing delay is increased, which leads to the increase of combustion noise. However, if the injection time is set too late, when fuel enters the chamber both the temperature and pressure become lower, and accordingly the firing delay is increased, which leads to the increase of combustion noise. An optimal time exists for injection delay.
3. Pre-injection: pre-injection has the function of separating the injection process into two stages, which allows fuel to be injected twice instead of once within one cycle [50].

In the first stage, a small portion of fuel is injected to precede the pre-reaction of firing before a major injection, to reduce the quantity of combustible fuel accumulated during combustion delay. This is an effective approach to reduce the noise of the direct-injection diesel. Improve the structure, layout, and parameters of the combustion chamber: the formation of the air mixture and combustion is influenced by the structure and layout of the combustion chamber, which not only affects the performance of the diesel, but also affects the firing delay, the rate of pressure rise, and thus the combustion noise. For the same condition, the sphere combustion chamber and biased cylinder chamber of the direct-injection diesel engine yield comparatively lower combustion noise [51]. A diesel engine with a separation chamber generally has lower noise. The optimization of the parameters of the combustion chamber can reduce combustion noise. Compared with the lower crankcase, the cylinder and cylinder head are usually very stiff, which allows them to resist the combustion pressures and prevent them from movement. It has been found that some special structure designs can attain better stiffness performance, including a lower crankcase, flat panels on the upper crankcase, and optimal substructures for oil pan and valve cover, etc. [52].The extra ribs applied to reinforce crankcase walls could reduce noise. It has been estimated that the total engine noise can be reduced by 3 dB by using the treated covers (sump, valve cover, etc.). The crankcase walls and the main bearing caps have been integrated to form a ladder-type structure [53].

Optimization of fuel pump: the injection rate has a significant effect on combustion noise. Certain experiments have illustrated that doubling the injection rate increases combustion noise by 6 dB. Therefore, the combustion noise can be reduced by decreasing the injection rate of the fuel pump. But this approach may worsen the high-speed performance and increase idle noise. Employ turbocharging techniques: turbocharging can increase the density of the air entering the cylinder, and increase the temperature and pressure of the air in the cylinder at the end of compression, thus improving the firing condition for the mixed gas and reducing the firing delay. The higher the turbocharging pressure, the shorter the firing delay period and the lower the pressure elevation rate, thus the lower the combustion noise. Some experiments have demonstrated that turbocharging allows combustion noise to be reduced by 2 to 3 dB.

Increase compression ratio: increasing the compression ratio can increase the gas temperature and pressure at the end of compression, shorten the period of firing delay, and reduce the pressure rise rate, thus reducing combustion noise. On the other hand, increasing compression ratio could increase cylinder pressure and increase piston slap noise.

Increase the quality of fuel: some ingredients in fuel may influence the physical and chemical processes of the gas mixture before firing, thus leading to a change in firing delay. Therefore, some high-quality fuel gives rise to short firing delays, thus lowering the pressure rise rate and the combustion noise.

Electronic control: a diesel engine with electronic control injection can optimize injection in terms of speed, load, air temperature, turbocharging pressure, and fuel temperature, thus effectively reducing combustion noise. The common rail injection system has been applied widely. The application of common rail injection can help to reduce the injection rate in the first injection period. The high frequency vibrations improve after the application of common rail injection, thus reducing combustion noise. Advantages of the common rail injection system are that the injection pressure is independent of engine load and speed, there are multiple timing and injection volumes, a variable profile of injection rate, flexible design, less constraints of cylinder number, and improved start-up properties.

4. MOTION BASED NOISE

Mechanical noise of the engine is referred to as the vibration- or impact induced noise of motion components of the engine under the effect of cylinder gas pressure and inertia forces [54].Mechanical noise of the engine consists of piston slap noise (it has also been referred to as indirect combustion noise), gear noise, valve train and timing system noise, accessory noise, bearing noise, block structure noise, etc. [55]. Mechanical noise is usually the main noise source of the engine in high-speed operations. A typical engine has several hundred moving pairs. In operation, the impact, friction, wear, and unbalance in rotation result in vibration and noise. The resonance due to the coincidence of natural frequency and excitation frequency leads to severe noise [56]. In the reciprocating motion process of the engine crank/piston, when it passes the upper or lower dead ends, the transverse force changes direction. [57]. This allows the contact zone between piston and cylinder to switch from one side to the other, which induces impact and cylinder vibrations. Each moving pair has a certain gap, which results in impact when it undergoes oscillatory motion; for intake or exhaust valves in alternative closing and opening motions, when the valve seats, it creates impact and noise[58]. The frequency of vibration depends on the number of valve operations per second. In general, the mechanical noise of the engine increases rapidly with the increase of operational speed [59-60].With the application of a high-speed and light engine, and the implementation of more strict noise regulations, the major difficulty of reducing engine noise lies in the reduction of mechanical noise.

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Authors` contacts:

Amar Singh
Shubham Bharadwaj
Sunny Narayan

Mechanical Engg Department
Indus University, India
E-mail: rarekv@gmail.com