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Analyzing the Sources of Noise in Internal Combustion Engines

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ABSTRACT

Internal combustion engines are extensively used in various modes of transportation, including ships and cars. However, their operation generated significant noise, which can disrupt daily life and poses health risks. Prolonged exposure to noise can lead to insomnia, cardiovascular diseases, and even death, making noise pollution a growing social concern. As the primary power source and major noise contributor in ships and automobiles, internal combustion engines play a crucial role in overall noise levels. The noise produced by internal combustion engines stems from various sources and mechanisms within the engine. These includes the combustion process itself, mechanical interactions between engine components, and the exhaust system, ect. Each of these sources have specific causes and contributing factors. This work discusses and analyzes the sources of noise, their causes, and the factors that influence them. By addressing these key areas, it is possible to reduce the negative effects of engine noise on human health and well-being.

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1. Introduction

Noise is unwanted or harmful sound, and is considered noisy or unpleasant to the hearing. Noise pollution is a growing issue, exacerbated by factors like population growth, urbanization, and higher levels of transportation. It is closely associated with health problems like elevated blood pressure, heightened stress, tinnitus, hearing impairment, sleep disturbances, and accelerated cognitive deterioration. Some specific kinds of loud sounds, like those generated by heavy manufacturing (exceeding 105 dB for an hour) or firearm noise (over 130 dB for a few seconds), can result in lasting damage to one's hearing [1]-[2].

For a healthy young individual, the audible range spans from 20 Hz to 20 kHz. The sound pressure level (SPL) at the border of this range fluctuates with frequency. Specifically, at 1 kHz, the SPL can vary from 0 to 130 dB. The human ear is greatest feeling within the frequency range of 500 Hz to 5 kHz, while it tends to be less responsive to sounds below 100 Hz (see Fig 1).

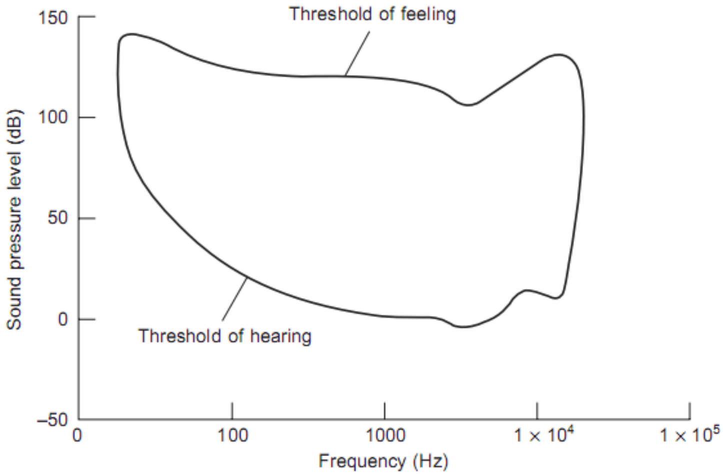

Figure 1. *The audible range [3], [4].*

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Engine noise levels usually range from 80 to 110 dBA when measured at a distance of 1 meter from the engine surface [5],The intensity of this noise is contingent upon factors such as engine size, speed, and injection system. Various elements within ICE contribute to its overall noise, including exhaust noise, intake noise, fan noise, combustion noise, piston slap noise, and valve system noise. The relative contributions of these sources to the overall sound pressure level of engine noise (at a distance of 1 meter from the engine) can vary significantly depending on operating conditions and the specific type of engine, as illustrated in Fig. 2 [6].

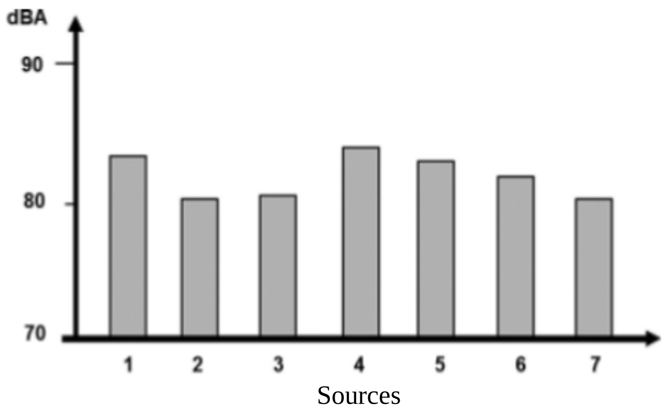
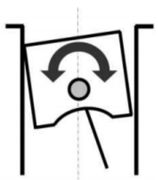


Figure 2. *Various sources contribute to the total sound pressure level of noise emitted by an engine, (measured at a distance of one meter from the engine) [6]. (1) exhaust noise; (2) intake noise; (3) fan noise; (4) combustion noise; (5) piston slap noise; (6) noise of accessories and belt; (7) valve system noise.*

In internal combustion engines (ICE), the generation mechanism of noise can be described as follows: When the combustible mixture undergoes compression and combustion in the engine's combustion chamber, it results in intense pressure changes. These dynamic loads impact all connected components, leading to complex structural vibrations. These vibrations are then transmitted through various engine parts, such as the cylinder cover, cylinder liner, and crank-connecting rod mechanism. Ultimately, the external surface structure of the engine radiates noise to the surrounding environment [7]. The noise generation process and transmission path in internal combustion engines are described in Table 1.

The noise sources within internal combustion engines can be categorized into two primary types: those originating from the combustion process and those resulting from mechanical impacts (refer to Table 1) [8]-[9]. Typically, the combustion process and mechanical interactions like piston slap are the predominant factors contributing to vibration and noise in an ICE.

Table 1. *The excitation on ICEs and their noise generation process [4], [10], [11].*

Force Generation	**Force Applied to Structure**	**Vibration Transmission**	**Noise Radiators**
Combustion	Cylinder Pressure Pulses	Cylinder Head	Rocker Cover Manifolds
		Piston Connecting-Rod	Crankshaft ICE Block
 Mechanical	Mechanical Impacts: • Piston Slap • Bearings • Valves • Fuel Pump	Cylinder Walls	Water Panels Side Covers Sump Timing Cover

Noise and vibration generated in the engine are mainly radiated from the outside parts of the engine. The radiated sound intensity P can be based on the following equation [10].

$$P = d.v.s.\mu_r.V^2 \tag{1}$$

With:

d = density of air

V = velocity of sound

s = radiation area

μ_r= radiation efficiency

V^2 =temporal and spatial average of the surface vibration velocity squared

2. Combustion noise

The noise produced during combustion stems mainly from swift shifts in internal cylinder pressure. This combustion sequence leads to dynamic loads because of rapid pressure alterations, high-frequency gas oscillations, vibrations, and pulse waves [12], [13]. The magnitude of noise originating from aerodynamic loads depends on maximum of the speed-duration of pressure elevation (dp/dt) and peak pressure. Experimental observations show that the intensity of combustion noise correlates with cylinder pressure [12].

$$I \sim [P_{max}(dp/dt)_{max}]^2 \tag{2}$$

Where:

I: the sound intensity of the combustion noise; P_{max}: pressure peak in the cylinder; and $(dp/dt)_{max}$: the maximum rate of pressure rise.

The pressure in a diesel engine's cylinder exceeds that of a gasoline engine, with a higher maximum rate of pressure increase. In particular, a diesel engine encounters a pressure increase rate ranging from 0.3 to 0.6 MN/m^2/crankshaft angle, roughly three times higher than that of a gasoline engine [14]. As a result, the noise produced by a diesel engine is significantly louder than that of gasoline engines [13]-[15].

2.1. Knock in gasoline engine

In gasoline engines, combustion noise typically constitutes a minor portion of the overall noise. However, when combustion knock occurs, it generates a flame front with a propagation speed that is 10 to 100 times faster than that associated with normal combustion initiated by the spark plug (which is around 20m/s) [16]. Detonation fire depends on the time it takes to spread the flame film to a location capable of causing detonation and the time needed to form a self-igniting center. Detonation will not occur if the flame spreads before the unburned gas mixture has enough time to cause spontaneous combustion [17]. This uncontrolled burning creates pressure waves that spread in circular patterns from the heart of the reaction. Knocking occurs near the top center during combustion, leading to increased peak pressure and pressure fluctuations in the cylinder. It is the collision of these pressure pulses with the cylinder walls that generates the metallic pinging sound. Engine knocking can occur at various speeds but is often not heard at high RPMs due to other engine noises.

Detonation in gasoline engines is often affected by the following key factors [16]:

- Ignition timing: Advancing the ignition timing increases combustion chamber temperature and peak pressure.
- Cylinder-charge density: Higher torque demand requires increased charge density, leading to higher compression temperatures.
- Fuel quality: Using low-octane fuels can raise the risk of knock so following the manufacturer's recommended fuel grade is crucial.

- Excessive compression ratio: Issues like a thinner cylinder head gasket can raise pressures and temperatures during compression. The presence of deposits within the combustion chamber can also influence the compression ratio.
- Cooling system efficiency: Poor heat dissipation can result in high temperatures in the combustion chamber.
- Engine geometry: Unfavorable combustion chamber geometry and improper intake manifold configuration can lead to poor mixture turbulence and swirl, increasing the engine's detonation tendency.

2.2. Knock in diesel engine

Diesel engines operate without an externally supplied ignition spark. Instead, high-pressure fuel is injected into the combustion chamber towards the end of the compression stroke, forming a heterogeneous mixture. Combustion ensues when the pressure and temperature within the combustion chamber surpass the self-ignition conditions of the fuel [17].

The period between fuel injection and combustion is termed the combustion delay time. A prolonged delay time leads to increased fuel accumulation within the combustion chamber and a buildup of heat. Consequently, combustion occurs rapidly, causing a sharp rise in pressure within the combustion chamber, impacting the surrounding components. This rapid and intense combustion process manifests as engine knocking sounds [18].

The large combustion delay time depends on the following main factors:

- Cold engine or large heat loss.
- Fuel injection timing is too early.
- Low self-ignition index of the fuel (low cetane index).
- The fuel may not be adequately atomized, or the fuel injection pressure might be insufficient.

Pre-injection effectively relieves the sudden increase in combustion pressure. When a small amount of fuel (approximately 1 mg) is burned during the compression phase, it raises the pressure and temperature in the cylinder. As a result, the ignition delay for the main injection is shortened, positively impacting combustion noise [19].

2.3. The impact of various parameters on combustion noise

2.3.1. Fuel quality

In diesel engines, the cetane number significantly influences cylinder pressure development and ignition delay. Fuels with low cetane values result in a prolonged combustion delay, leading to higher rates of pressure rise and maximum peak pressure, ultimately increasing combustion noise.

The octane rating of a gasoline fuel indicates its resistance to detonation. A higher octane rating corresponds to a higher resistance to detonation in the engine. During engine operation, it is necessary to increase the octane of the fuel. This can be explained as follows, after a period of operation the soot layer formed in the engine combustion chamber does little to change the compression ratio, but significantly increases the temperature of the wall within the combustion chamber, thus increasing the heat transferred to the mixture during the intake cycle. Therefore, it increases the possibility of detonation. For car engines, after running about 15.000 - 25.000 km, the octane number needs to increase about 5 units [17], [20].

2.3.2. Load

Essentially, as the load increases, more fuel is burned, resulting in greater heat release. This elevation in combustion pressure peak and pressure rise rate also occurs. However, with the rise in combustion chamber temperature, the gap between the cylinder wall and piston diminishes, potentially resulting in reduced noise levels [12].Considering the possibility of detonation in a diesel engine, when increasing the load on a diesel engine (using undivided combustion chamber), the combustion delay time decreases almost linearly. It can be explained as follows: when the load increases, the combustion chamber wall temperature and residual gas temperature will increase, increasing the temperature of the new charge mixture. The above effects will reduce the combustion delay time [17], [20].

2.3.3. Engine speed

In a diesel engine, if the combustion delay time is measured in milliseconds, increasing the engine speed while maintaining the load will shorten the combustion delay time. This phenomenon can be explained as follows: at higher engine speeds, the air leakage decreases, and fuel injection pressure rises. Additionally, the peak temperature during compression increases due to reduced heat loss. Consequently, the combustion delay time is shortened [17], [20].

In a spark ignition engine, at high speed, the air-fuel mixture has less time to overheat. Moreover, the pressure at the conclusion of the compression stroke, typically decreasing with higher engine speeds, presents fewer favorable conditions for detonation to take place. Conversely, the shorter time for combustion heat to dissipate will increase cylinder temperature. However, under the combined influence of the above factors, the occurrence of engine detonation tends to decrease as the engine speed increases [21].

2.3.4. Injection parameters

There are some injection parameters expressed as pre-injection, main injection, fuel quantity, pressure, and injection start [16]. An electronic controller unit calculates variables like temperature coefficient, engine speed, load, and altitude to achieve this precision. In common-rail injection systems, injection pressure remains virtually constant during the injection process. This pressure independence from engine speed allows for better control. The double injection technique (pre-injection and main injection) balances pressure rise and increases engine power [19].

GDI engines behave similarly to manifold-injected engines when operating with homogeneous air/fuel mixtures. In stratified-charge mode, only the area near the spark plug tip contains an ignitable mixture. The rest of the combustion chamber is filled with air or inert gases, eliminating the risk of spontaneous ignition and engine knock [16].

2.3.5. Turbocharge

Turbocharging an engine elevates the temperature and pressure of the intake air, consequently raising the temperature of the air/fuel mixture. In diesel engines, turbocharging decreases combustion delay time, thereby reducing combustion noise, especially under full load conditions. Intercoolers, commonly paired with turbochargers, serve to lower air charge temperature, thus reducing NOx emissions but potentially increasing the noise level of the combustion process [22].

2.3.6. Mixture ratio

Experimental results show that different air/fuel ratios (λ) will lead to different fire film propagation speeds. When λ is approximately 0.85 to 0.95, the flame film propagation speed reaches its maximum value. In this case, the temperature and pressure at the end of the flame film are very large, causing the unburned gas mixture to be strongly compressed, leading to its pressure and temperature increasing. This will lead to detonation [17], [23].

2.3.7. Ignition and injection timing

In gasoline engines, increasing the ignition advance angle leads to a loss of work during the compression process. Additionally, it raises the temperature of the air-fuel mixture at the end of the flame propagation zone, thereby increasing the tendency for detonation.

When increasing the injection timing on a diesel engine, fuel is injected into the low-pressure and low-temperature air mass, leading to a longer combustion delay time. Consequently, the rate of pressure increase (dp/dt) and the maximum pressure (P_{max}) rise, resulting in the emergence of engine noise [23].

3. Mechanical noise

3.1. Piston slap noise

One significant source of engine noise arises from the piston colliding with the cylinder walls. Within the engine's crank-slider mechanism, there exists a slight clearance between the cylinder wall and piston. The reciprocating motion generates reversible forces, including side thrust force from the connecting rod, causing the piston to move from one side to the other, colliding with the walls. These collisions result in vibrations and noise [24], [25].To reduce piston slap impact, methods such as piston pin offset, vertical shift of the piston center of gravity, crankshaft offset and increasing the number of piston rings are commonly employed [25]. Shenghao Xiao's research et al. shows that increasing the cylinder diameter, piston pin offset, and crankshaft offset values compared to the original design can reduce engine noise by 2dB [26].

3.2. Bearing clearance noise

In an operational internal combustion engine (ICE) crank mechanism, dynamic shock interactions occur between the mating parts as the pistons move within the cylinders and the crankshaft journals interact with the supporting main and crank bearings. One way to reduce mechanical excitations is by reducing clearances between its components. Experimental results from a 4-cylinder, 16 valve ICE gasoline engine with a 1,774 liter displacement show that decreasing the main bearings' diameter by 0,013 mm and 0,024 mm reduces the clearance. As a result of this reduction, the noise level at the measurement point (1 m from the geometric center of the right side of the ICE cylinder block) decreases by 0.8 dBA and 1.2 dBA, respectively [27].

3.3. Induction and exhaust system noise

3.3.1. Valve system noise

Induction and exhaust systems utilize valves with multiple parts and gaps between them. During operation, impacts occur and noise is generated, such as the impact between the intake valve, exhaust valve, and their respective seats.

3.3.2. Intake noise

Intake noise arises from the intermittent airflow passing through the engine's intake system, which induces pressure pulses in the intake manifold. This noise then propagates through the air filter and is discharged from the intake manifold. It is dependent on engine load and typically ranges from 10 to 15 dB (from idle to full load) [4]. To reduce intake noise, a resonator is often integrated into the air intake manifold, which works according to the Helmholtz resonance principle. Its purpose is to change the resonance frequency of the airflow in the intake system, causing the resonance point of the intake noise frequency to be outside the normal operating speed range of the engine [3], [4].

3.3.3. Exhaust noise

Exhaust noise results from the abrupt discharge of exhaust gas during valve opening and closing. Its intensity and features vary considerably based on factors such as engine type, valve configuration, and timing. In particular, the intensity of the noise depends greatly on the load of the engine. When the load changes (from no load to full load), the noise level can change by 15dB [4].

Reducing engine intake and exhaust noise involves devices that reduce sound waves while maintaining airflow. These devices serve as sound filters, categorized as dissipative or reactive types [27]. Mufflers typically combine both types. Dissipative silencers absorb sound energy, while reactive silencers increase exhaust back-pressure, leading to some power loss [28], [29]. Additionally, adjusting the pipe size, adding a Helmholtz resonator to the intake pipe, and implementing turbocharging all contribute positively to reducing engine noise [30].

3.4. Fan noise

Low-speed rotating axial and radial fans are commonly employed to regulate engine temperature by facilitating sufficient airflow through heat exchangers, particularly during low vehicle speeds or idle. However, an unintended consequence of these fans is the generation of flow-induced noise, which can be bothersome to operators and passengers and can contribute significantly to community noise, especially in the case of commercial vehicles and heavy equipment. In many instances, especially with high mass flow configurations, the cooling fan emerges as a primary contributor to overall noise levels, occasionally overshadowing other sources like the engine, transmission, tires, mechanical components, or exhaust systems [31].

Cooling system noise escalates with increases in engine load and speed, often standing out as a primary source of noise. Traditional research has primarily concentrated on altering parameters such as the fan hub ratio, blade profile, blade installation angle, and blade number [32]. Shuwen Wang et al. introduced a bio-inspired structure featuring three ribbed ridges distributed concentrically to the fan hub axis, aimed at guiding airflow across the fan blade. This design exhibited the most significant noise reduction effect within the speed range of 1500 to 2500 r/min, with a reduction of 3.83 dBA compared to the original design [32].

4. Conclusions

This study delved into the intricate mechanisms underlying noise generation in internal combustion engines. The combustion process itself, marked by sudden increases in cylinder pressure, stands as a primary noise source. Furthermore, vibrations and movements of engine components like pistons, valves, and gears contribute significantly to overall noise output. Various factors including engine design, fuel quality, load, engine speed, etc. influence noise levels. In diesel engines, cylinder pressure surpasses that of gasoline engines, with a notably higher maximum pressure increase rate, resulting in greater explosion noise. Employing an engine control system proves pivotal in noise reduction. Additionally, techniques such as turbocharging, intake noise reduction, exhaust manifold noise reduction, and fan noise reduction contribute positively to overall noise reduction. However, implementing these techniques may complicate engine structures, increase costs, and potentially affect other engine characteristics.

Conflict of Interest

The author declares no conflict of interest.

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