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Investigation of the effect of camshaft profiles designed with the circular arc curve method for a common rail dual fuel engine on mechanical vibration and noise emissions

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Abstract

In this study, the design and manufacturing of cam profiles with different valve lifts were carried out using the geometric spring curve method for a single-cylinder, four-stroke common rail diesel engine. Subsequently, the impact of the designed cam profiles on vibration and noise emissions in conventional diesel combustion was examined. The effects of the cam profiles obtained using the circular spring curve method and fitted with Fourier series on the tappet's speed, acceleration, and leap were examined, and then the cam profiles to be manufactured were determined. Experimental tests were conducted on vibration and noise emissions using the manufactured cam profiles with pure diesel fuel at five different engine loads and a constant engine speed. When the results are examined, increasing the valve lift amount compared to the original cam resulted in an approximate 24% increase in vibration level, while decreasing the valve lift amount reduced the vibration level by approximately 20%. the effect of cam profile modification on average noise emissions was quite evident.

Keywords: Camshaft design, Diesel engine, Noise emissions, Valve lift, Vibration

Research Article

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1. Introduction

As the economy and population grow, the issue of air pollution becomes increasingly critical. Reducing fuel consumption and minimizing exhaust emissions from internal combustion engines is now more important than ever. Despite the development of gas vehicles, electric vehicles, and hybrid vehicles, those equipped with an internal combustion engine (ICE) remain the primary mode of transportation [1].

Sustainability and societal development rely on energy as a fundamental requirement. Fuel is a rich source of energy that is used extensively in our daily lives. However, with the growing demand and expansion of power sectors worldwide, traditional sources of fuel are being depleted at an accelerating rate. Researchers are increasingly focusing on alternative fuels as one solution to these issues. The world is shifting towards alternative fuels and engine modification (piston shape design, variable valve timing, lift, etc.) due to growing concerns over environmental pollution, particularly air pollution and global warming. The main sources of these problems are nitrogen oxides, particulate matter, carbon dioxide, and other pollutants that result from the combustion of traditional fossil fuels [2, 3].

Diesel engines are preferred in both land and sea transportation due to their high efficiency, versatility, and durability. Additionally, they are also widely utilized in power generation and industrial applications [4]. The extensive use of diesel engines results in harmful exhaust emissions that have a significant impact on both the environment and human health, raising serious concerns [5]. To reduce harmful exhaust emissions generated during combustion in diesel engines and improve engine performance, alternative gaseous fuels such as methane [6-8], natural gas [9, 10], biogas [11, 12], and hydrogen [13] are used in dual-fuel mode. The dual-fuel concept in diesel engines is generally achieved by using gaseous fuel and pilot diesel fuel. Gaseous fuels with high self-ignition temperature and low cetane number, such as methane, biogas, natural gas, and hydrogen, require an additional ignition source in diesel engines due to their weak ignition properties [14-17]. Based on the method of introducing gas into the cylinder and the ignition source, there are two primary methods for utilizing gas in a diesel engine. The first method is to intake the gas fuel into the intake manifold by using a gas injector or by sucking it in through the intake manifold to create a homogenous mixture with air. In this way, the gas fuel is taken into the cylinder by forming a homogenous mixture with air and ignition is achieved by injecting pilot diesel fuel onto it towards the end of compression [8, 18, 19]. In the second method, a small amount of pilot diesel fuel is injected into the combustion chamber, followed by the injection of gas fuel into the cylinder at high pressure. This method is known as high-pressure direct injection (HPDI) [17, 20-22]. The HPDI mode utilizes a stratified combustion technique, where natural gas is directly injected and burns in a primarily non-premixed combustion [23]. This approach enhances fuel efficiency and combustion efficiency, while also preserving the power output and thermal efficiency of a traditional diesel engine of comparable size [24, 25]. On the other hand, utilizing the HPDI mode requires a unique concentric-needle, dual fuel injector [24], which has a more complex structure and higher cost compared to the low-pressure gas induction or injection system required for dual fuel mode. Additionally, controlling the HPDI mode can be more challenging than the dual fuel mode. Implementing the dual fuel mode in existing diesel engines is relatively simple and does not require extensive modifications. This approach has been extensively studied and researched worldwide [17].

Methane, natural gas, and biogas, as gas fuels, contribute to the reduction of smoke and nitrogen oxides (NO_x) emissions when implemented in a dual-fuel mode in diesel engines [8, 26, 27]. However, when these types of gas fuels are used in dual-fuel mode, they bring along a series of problems. The most significant one is that gas fuels, due to their different physicochemical properties compared to diesel fuel, alter the combustion characteristics of the engine. In methane-diesel dual-fuel studies, there are issues such as high levels of hydrocarbon (HC) and carbon monoxide (CO) emissions and low combustion stability resulting from the high usage of methane [28]. HC and CO emissions are products of incomplete combustion, and a decrease in the amount of air in the cylinder plays a leading role in the increase of both emissions. Additionally, HC emissions are also influenced by non-homogeneous mixture and low internal cylinder air flow movements [29]. When considering the formation mechanisms of these emissions, altering the intake valve lift amount can have a significant impact on these emissions. The increasing or decreasing trend of valve lift not only affects the amount of air taken into the cylinder but also influences the flow motion to occur in a turbulent or non-turbulent manner.

The camshaft used in ICE is a mechanical component that transmits force to the intake and exhaust valves, enabling their opening, thanks to the cam lobes on it. The opening manner and timing of the valves vary depending on the design of the cam profile. In ICEs, mechanical efficiency is a crucial parameter, and an increase in engine speed leads to an increase in noise, vibration, friction, and inertia forces, thereby reducing engine efficiency. The decrease in mechanical efficiency not only negatively affects engine performance but also reduces the lifespan of mechanical components and can generate high levels of vibration and noise emissions. Cam profiles that determine the lift amount, opening time, and duration of the intake and exhaust valves can be designed using six different methods: sinusoidal cam curves, splines, trapezoidal profiles, cubic splines, B-splines, and trigonometric functions. In today's conditions, while methods for profile design based on kinematic and design optimization are being developed, approaches for conducting dynamic analysis of these profiles are still being improved. Fourier series is also a method used in cam profile design and is frequently employed by researchers to carry out cam profile design [30-35].

When designing a cam profile, the effects of valve lift and valve open duration on velocity, acceleration, and bounce are generally examined. Karabulut and Sarıdemir [35] focused on the impact of valve lift and valve open duration on velocity, acceleration, and bounce in their cam profile design using the classical spline method. Cinar and Uyumaz [30] conducted cam design for an homogeneous charge compression ignition (HCCI) engine using two different methods: a fifth-degree classical spline and a Fourier series extrapolated circular arc curve. They compared these two methods with each other. In the cam profiles designed with the fifth-degree classical spline method, it was determined that as the valve lift increases, the velocity, acceleration, and bounce values of the follower gradually increase, and the contact between the profile and the follower decreases at a single point. On the other hand, in the other method using the Fourier series extrapolation, it was found that the contact surface of the follower does not disappear, and the friction and inertial forces decrease. On the other hand, there are studies in the literature that perform cam profile design and analysis using methods such as classical spline [36], B-spline [37], three-circle arc curve [38, 39], and computer-based genetic algorithm [40] for cam profile design.

There are studies on both engine vibration and noise emissions, as well as engine performance, related to the valve lift amount and timing in ICE. In their study, Sarıdemir and Saruhan [41] experimentally investigated the effects of valve lift on engine noise and vibration. The experimental study revealed that as the engine speed increased, the inertial forces also increased, resulting in higher amplitude values for both valve lift amounts. It was noted that increasing the valve lift further amplified the amplitude values, leading to an increase in vibration levels. The study emphasized that the increased vibration levels and the occurrence of high amplitude values were attributed to severe collisions during the cam profile's bounce motion. On the other hand, He et al. [42] investigated the effects of reducing the valve lift and valve opening duration on the performance of a single-cylinder HCCI engine. It was determined that in the case of early closure of the exhaust valve, a certain amount of residual gas remains in the cylinder and occupies the space intended for intake air. Consequently, it has been observed that the mass of air taken into the cylinder is reduced. Zhang et al. [43] conducted a study on the lift and timing of valves in HCCI engines. In the study, 9 different valve lifts ranging from 9.5 mm to 0.5 mm were used. When the results were examined, it was reported that decreasing the valve lift increased the amount of trapped residual gas in the cylinder. Cinar et al. [44] examined the effect of two different cam profiles with valve lift values of 7 mm and 8 mm on the engine performance and exhaust emissions in an liquefied petroleum gas (LPG) and gasoline-fueled spark ignition (SI) engine. The study determined that increasing the intake valve lift led to an increase in volumetric efficiency and improved engine performance. Gültekin et al. [45] reported that increasing the intake valve lift by 10% in a hydrogen/diesel dual-fuel engine resulted in a 40% reduction in soot emissions and a 33% reduction in CO emissions. Additionally, it was noted that engine performance improved. Bayramoğlu et al. [46] numerically examined the effect of intake valve lift on engine performance. The results showed that an increase in intake valve lift improved combustion behaviour due to the increase in volumetric efficiency. It was determined that CO emissions decreased while NO emissions increased. In the study conducted by Gong et al. [47], the impact of intake valve lift amounts under different injection strategies on knocking and performance was investigated. It was reported that increasing the intake valve lift during late-second injection conditions and decreasing the intake valve lift during early single injection conditions resulted in a more homogeneous mixture and reduced wall wetting. Additionally, it was reported that these two conditions led to faster flame propagation and improved combustion efficiency. Cinar et al. [48] examined the effect of four different valve lift combinations (intake and exhaust) at various air/fuel ratios and intake air temperature conditions to improve the performance and emission characteristics of an HCCI engine. The results indicated that reducing the valve lift improved performance in the regions where knocking was observed in the HCCI engine, and it was mentioned that the operating range of the HCCI engine could be expanded as a result.

As observed, although there are studies in the literature regarding the design and manufacturing of cam profiles and their effect on performance and emissions, there is no study experimental research on the effect of these cam profiles with different valve lift values on engine vibration and noise. Therefore, conducting a study in this area would contribute to the literature and fill this gap.

In this study, the design and manufacturing of a cam profile that enables the variation of the intake valve lift were carried out for a single-cylinder, four-stroke, common rail dual-fuel engine, and the effect of these valve lifts on engine vibration and noise was investigated. The purpose of this study is to examine the effect of different valve lift profiles on engine mechanical vibration and noise emissions by designing them using the circular spring curve method. In the literature, the absence of an experimental study including the effects of different valve lift amounts on engine vibration and noise has encouraged the execution of this study in order to serve as a reference for future research and shed light on the subject. In the study, the geometric model of cam profiles with five different valve lift values was obtained using the circular arc method, and extrapolated using Fourier series. The velocity, acceleration, and leap values of cam profiles fitted with Fourier series were examined. Considering the velocity, acceleration, and leap values, as well as the engine construction, cam profiles to be manufactured were determined. Subsequently, the effects of the manufactured cam profiles on vibration and noise values were investigated under five different engine loads and a constant engine speed.

2. Material and Method

2.1 Material

In this study design and fabrication of cam profiles with different valve lift amounts were carried out. The effects of cam profiles with different valve lift amounts, which were fabricated, on vibration and noise emission were experimentally investigated. The schematic representation of the experimental study is presented in Fig. 1.

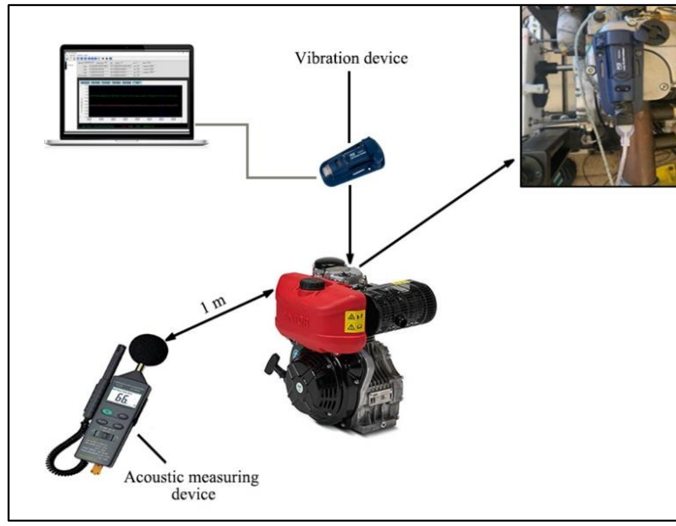

Fig. 1. The schematic representation of the experimental study.

A single cylinder, air-cooled, common rail engine was used for the vibration and noise emission experiments. The technical specifications of the engine used in the study are presented in Table 1. To simulate the common rail diesel engine, an ABB brand DC dynamometer with a maximum power of 50 kW and a torque of 157 Nm, equipped with an air-cooling system, was employed for the engine braking.

Table 1. Technical specifications of the common rail dual-fuel engine [8].

Specifications	**Antor AD320**	
Engine type	Gas/diesel dual-fuel engine	
Engine displacement	315 cm^3	
Bore and stroke diameter	78 mm and 66 mm	
Compression ratio	17.3:1	
Max. engine torque (speed)	11 Nm (1850 rpm)	
Injection timing/pressure	349 CAD/500 bar	
Fuel supply system	Gas	Diesel
	Intake manifold	CRDI

The oscillation generated by the diesel engine was measured using a vibration measurement device. The vibration device was mounted on top of the engine head. The data was recorded using the PCE-VD3 model accelerometer vibration device. The vibration device is a compact universal data logger. Vibration measurements are taken in g (m/s^2) units using an accelerometer device. This device performs measurements in the X, Y, and Z axes, calculating the vectorial average of these coordinates. The integrated sensor in this device has a measurement range of ±18 for each axis. For each cam profile experiment conducted with standard diesel fuel, experiments were repeated three times, and vibrations of coordinates X, Y, and Z were recorded for each experiment for two minutes each. Subsequently, the average of these data was taken and compared for different cam profiles. The noise emission generated by the common rail diesel engine was measured using the GERATECH DT 8820 model sound level meter, as shown in Fig. 1, in decibels (dBA). The measurements were conducted in accordance with the ISO 3746:2010 standard [49], at a distance of 1 meter from the noise source and in an enclosed environment. The measurements were conducted in a closed environment, using a free-field measurement approach. Assuming the presence of a half-sphere with a one-meter radius around the engine, measurements were taken at specific intervals within this sphere using a free-field microphone. The average of the instantaneous maximum and minimum noise measurements taken over a 120-second period was calculated. Experiments were conducted three times for all experimental parameters, and the data obtained in this experimental study were analyzed by taking the average of the results.

2.2 Method

2.2.1. Camshaft profile design

In dual-fuel engines, increasing the intake of a greater amount of air mass into the cylinder and promoting turbulent flow can be seen as ways to minimize HC and CO emissions. The turbulent flow inside the cylinder ensures a homogeneous distribution of the air-fuel mixture and contributes to the rapid advancement of the flame front during the expansion stroke. A decrease in the oxygen level inside the cylinder results in increased CO and HC emissions. Therefore, increasing the oxygen content inside the cylinder will lead to a reduction in these emissions. The amount of air taken into the cylinder can be increased by adjusting the valve lift. Additionally, the valve lift, especially during the intake phase, can contribute to the formation of turbulent airflow inside the cylinder [29, 50].

Table 2. Original camshaft profile specifications of the common rail dual-fuel engine.

Specifications	Value	
Basic bore diameter	14.5 mm	
Intake valve open duration [28]	232 Crank Angle	
Valve lift amounts	Intake	Exhaust
	4.46 mm	6.18 mm

In cam profile design, classical spline and circular spring curve methods are commonly used techniques [51]. However, in a study conducted by Cinar and Uyumaz [30] on cam design and manufacturing, it was reported that cam profiles designed using classical spline functions lose the tappet contact feature and experience excessive increases in acceleration and rebound values as the valve lift increases. On the other hand, in the cam profiles designed with a circular spring curve, it was reported that despite the valve lift, the tappet retains the contact feature at a single point, and friction and inertia forces are reduced. Therefore, considering the performance of the circular spring curve method, in this study, cam profiles were obtained using the circular spring curve method and extrapolated with a Fourier series. The camshaft specifications are provided in Table 2.

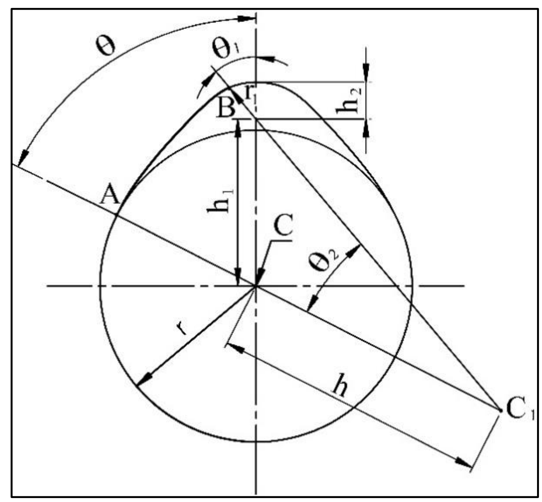

Fig. 2. Design parameters of the cam profile designed using the circular arc curve [30, 52].

One of the most preferred methods in cam profile design is the circular arc method [30, 39]. Fig. 2 illustrates the design parameters of the cam profile designed using the circular arc method. Where, θ represents the valve opening duration, θ_1 represents the maximum angle of the second circular arc, θ_2 represents the maximum angle of the first circular arc, h_2 represents the maximum valve lift, and r represents the base circle radius [52].

The cam peak radius and the centre distance are calculated using equations (1) and (2) respectively. The angles θ_1 and θ_2 are calculated following equations (3) and equations (4) respectively.

$$r_1 = r + h_2 - h_1 \tag{1}$$

$$h = \frac{h_1^2 - (r - r_1)^2}{2 \times (r - r_1 - cos\theta)} \tag{2}$$

$$sin\theta = \frac{h_1 \times sin\theta}{h + r - r_1} \tag{3}$$

$$\theta_1 = \theta - \theta_2 \tag{4}$$

To extrapolate cam profiles with different valve lifts using the circular arc method with a Fourier series, equations (5) and (6) are followed. By determining the coefficients, a_m and b_m in equation (5) adequately, equation (6) is derived to fit the motion function of the camshaft using the Fourier series. Taking the derivatives of equation (6) yields the functions for the follower's velocity, acceleration, and leap.

$$f(x) = \frac{a_0}{2} + \sum_{m=1}^{n} (a_m cosmx + b_m sinmx) \quad (5)$$

$$f(I) = \frac{a_0}{2} + a_1 cos(T(I)) + b_1 sin(T(I)) + a_2 cos(2T(I)) + b_2 sin(2T(I)) + \cdots \quad (6)$$

Fig. 3 presents the variation of valve lifts with respect to cam angle for cams designed using the circular arc method and extrapolated with Fourier series. The valve lift amounts of cam profiles designed using the circular spring method are represented by the abbreviation "VL," while the valve lift amounts of cam profiles fitted with Fourier series are expressed as "VLF." It is observed that the valve lift values obtained from cam profiles designed using the circular arc method and the values fitted with the Fourier series are significantly close to each other, indicating a homogeneous and smooth motion.

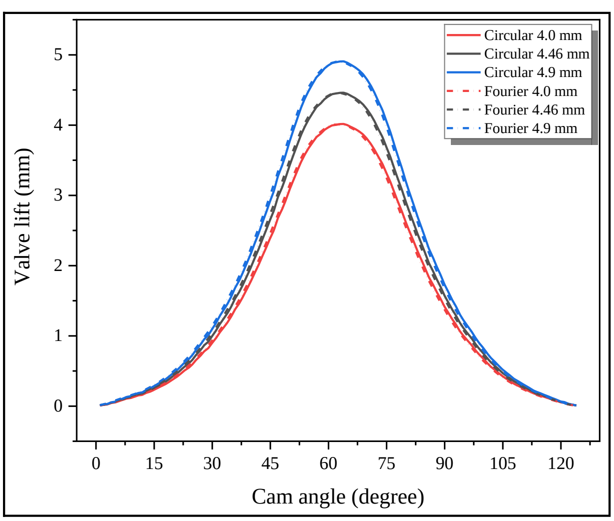

Fig. 3. Valve lift of the cams designed with the circular arc curve method and extrapolated with the Fourier series.

Fig. 4 illustrates the comparison of speeds at an engine speed of 1850 rpm for different cam profiles with valve lifts fitted using the Fourier series. At the maximum and minimum valve lift points of the cam profile, the velocity of the lifter is 0. As the valve lift increases, the velocity of the lifter also increases. The maximum velocity of the cam profiles fitted using the Fourier series are as follows: The velocity of VLF-4.0 mm is 537 mm/s, the velocity of VLF-4.46 mm is 597 mm/s, and the velocity of VLF-4.9 mm is 657 mm/s.

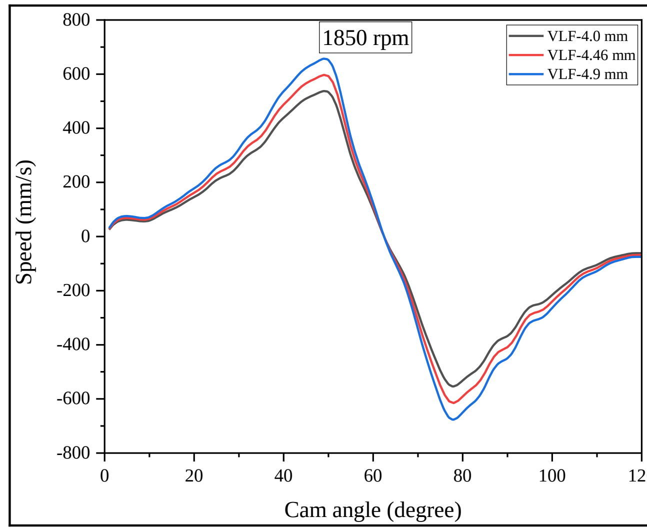

Fig. 4. Comparison of the speeds of cams with different valve lifts.

Fig. 5 illustrates the comparison of accelerations at an engine speed of 1850 rpm for different cam profiles with valve lifts fitted using the Fourier series. As observed in the figure, as the valve lift increases, the lifter experiences acceleration. The highest acceleration is obtained with the cam profile having a valve lift of VLF-4.9 mm, while the lowest acceleration value is obtained with the cam profile having a valve lift of VLF-4.0 mm. The maximum acceleration of the cam profiles fitted using the Fourier series are as follows: The acceleration of VLF-4.0 mm is 549 mm/s^2, the acceleration of VLF-4.46 mm is 610 mm/s^2, and the acceleration of VLF-4.9 mm is 671 mm/s^2. Fig. 6 illustrates the comparison of leaps at an engine speed of 1850 rpm for different cam profiles with valve lifts fitted using the Fourier series. As the valve lift increases, similar to the velocity and acceleration values, the leap values of the lifter also increase. The highest leap is obtained with the cam profile having a valve lift of VLF-4.9 mm, while the lowest leap value is obtained with the cam profile having a valve lift of VLF-4.0 mm. The maximum leap of the cam profiles fitted using the Fourier series are as follows: The leap value of VLF-4.0 mm is 6013 mm/s^3, the acceleration of VLF-4.46 mm is 6682 mm/s^3, and the acceleration of VLF-4.9 mm is 7350 mm/s^3.

As observed in the speed, acceleration, and leap values, an increase in valve lift leads to an increase in these values. In the literature, it is mentioned that higher acceleration of the lifter can cause high vibrations in the valve system, necessitating the use of stronger springs. The increase in acceleration of the lifter also increases the friction force and accelerates the wear of the cam mechanism [30, 34, 35]. In this case, it is thought that cam profile designs with lower acceleration would reduce both vibration and wear.

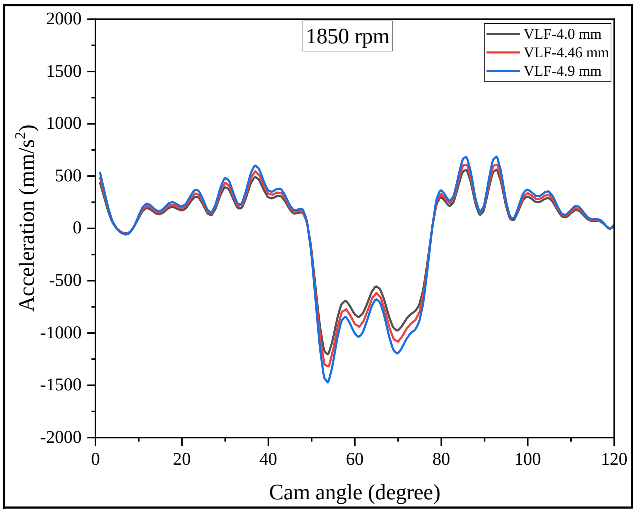

Fig. 5. Comparison of the accelerations of cams with different valve lifts.

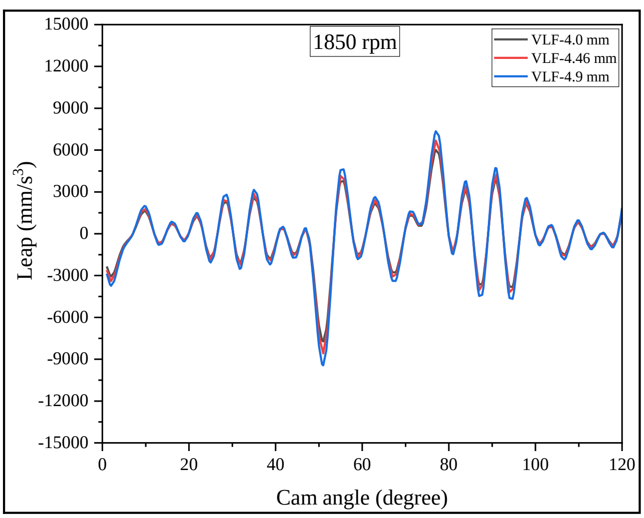

Fig. 6. Comparison of the leaps of cams with different valve lifts.

Considering the obtained results, there is a similarity with the results of the camshaft design and manufacturing study conducted by Cinar and Uyumaz [30]. However, the acceleration and leap values of the cam profiles designed and fitted using the circular arc method and Fourier series in the study conducted by Cinar and Uyumaz are significantly higher than the acceleration and bounce values obtained in this study. Therefore, there is no concern regarding the manufacturing of the cam profiles with valve lifts of 4.0 mm, 4.46 mm, and 4.9 mm as designed.

2.2.2. Camshaft profile manufacturing

A camshaft mechanism was manufactured for a single-cylinder, four-stroke, air-cooled, common rail dual-fuel engine in order to modify the valve overlap duration by introducing threads, thereby enabling the alteration of valve timing. In Fig. 7, the camshaft mechanism is presented.

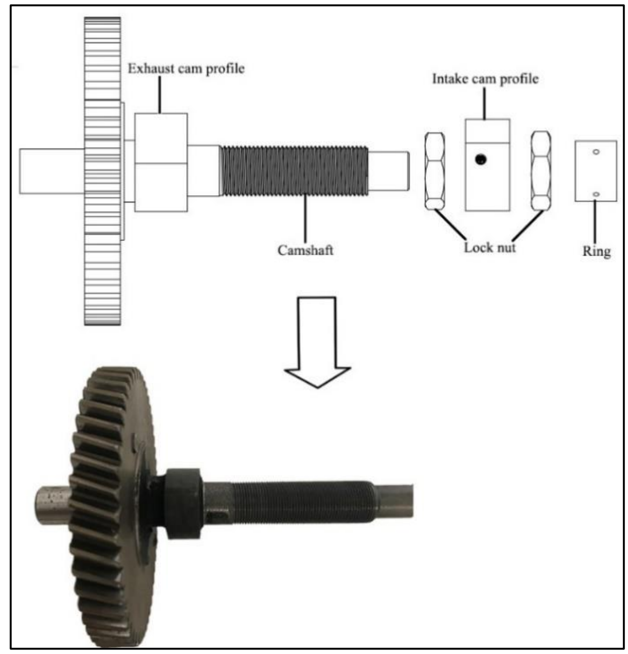

Fig. 7. Camshaft mechanism.

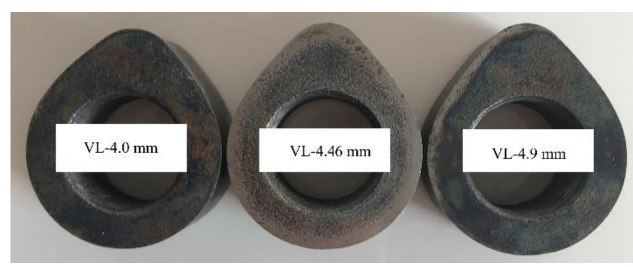

Fig. 8. Cam profiles with different valve lift amounts produced on CNC wire erosion machine.

The camshaft mechanism has been threaded in the opposite direction of the camshaft's movement, with an M18x1 thread, for the assembly of cam profiles and lock nuts. Similarly, the centers of the cam profiles and lock nuts have been threaded with an M18x1 thread. The cam profiles are made of Ç4140 material to withstand high impact and vibration and have undergone a hardening process up to 60 HRC. The cam profiles, designed using the circular arc method and fitted with Fourier series, were saved in DWG format in SolidWorks program and manufactured using CNC wire erosion machine. Fig. 8 presents the manufactured cam profiles with different valve lift: 4.0 mm (VL-4.0 mm), 4.46 mm (VL-4.46 mm), and 4.9 mm (VL-4.9 mm).

The manufactured cam profiles and lock nuts were assembled onto the variable camshaft mechanism without altering the valve opening and closing timing of the original engine. Subsequently, they were subjected to vibration and noise emission tests.

2.2.3. Experimental procedure

Average vibration and noise emission tests were conducted on a single-cylinder, four-stroke, air-cooled, common rail dual-fuel engine. The tests were performed at five different engine loads (3, 4.5, 6, 7.5, and 9 Nm) and a constant engine speed of 1850 rpm. In the experimental study, the variation of the constant 1850 revolutions per minute (rpm) engine speed with respect to the cycle was presented in Figure 9. The engine speed/cycle graph was obtained while performing the engine's original cam profile experiments. As can be seen, the single-cylinder, air-cooled diesel engine operated with a common rail fuel system exhibited a maximum deviation of ±5 rpm in engine speed for each engine load. Also, 1850 rpm is the maximum torque speed of the engine, and this choice was made to achieve higher efficiency and correspond to urban traffic speeds. To conduct the experiments, EURO diesel fuel was obtained from a local company. The study aimed to investigate the effect of valve lift variation on average vibration and noise emission and compare their respective impacts. The test matrix is presented in Table 3.

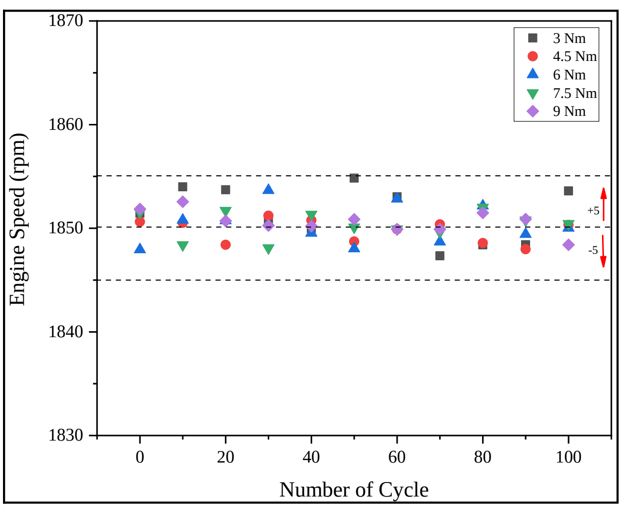

Fig. 9. The variation in engine speed with respect to cycle in experiments conducted with the original cam profile.

Table 3. Test matrix

Case	Valve lift (mm)	Fuel	Torque (Nm)	Speed (rpm)
VL-4.0	4	Diesel	3, 4.5, 6, 7.5, and 9	1850
VL-4.46	4.46			
VL-4.9	4.9			

3. Results

Fig. 10 illustrates the impact of varying valve lift amounts on average vibration under different engine load conditions. As observed in the Fig. 10, an increase in engine load has shown a decreasing trend in average vibration values for all valve lifts. The lowest average vibration values for all valve lifts were achieved under 9 Nm engine torque conditions, while the highest average vibration values were obtained under 3 Nm engine torque conditions. The primary reason for this phenomenon is the occurrence of more unstable combustion during low-load conditions, leading to increased engine vibration. On the other hand, an increase in load and combustion temperatures promotes a more stable combustion phase, resulting in lower engine average vibration values. Furthermore, under low-load conditions, less fuel injection occurs into the cylinder, which can lead to cycle-to-cycle variations. In a study by Gülcan and Ciniviz [8], it was reported that more significant cycle-to-cycle variations occurred under low-load conditions. However, under high-load conditions, the increased temperatures of the post-combustion gases improve combustion stability. A reduction in cycle-to-cycle variations leads to a decrease in the average engine vibration levels. On the other hand, an increase in valve lift amount compared to the original valve lift has resulted in an increase in average vibration values under all load conditions, while a decrease in valve lift amount has led to a decrease in average vibration values. The cam profile with a valve lift amount of 4.9 mm has caused approximately a 24% increase in average vibration values compared to the original valve lift amount of 4.46 mm. Conversely, the cam profile with a valve lift amount of 4.0 mm has resulted in approximately a 20% decrease in average vibration values compared to the original valve lift amount of 4.46 mm. As the valve lift amount increases in the cam profile, the contact surface with the lifter increases, and this can be said to cause an increase in engine vibration.

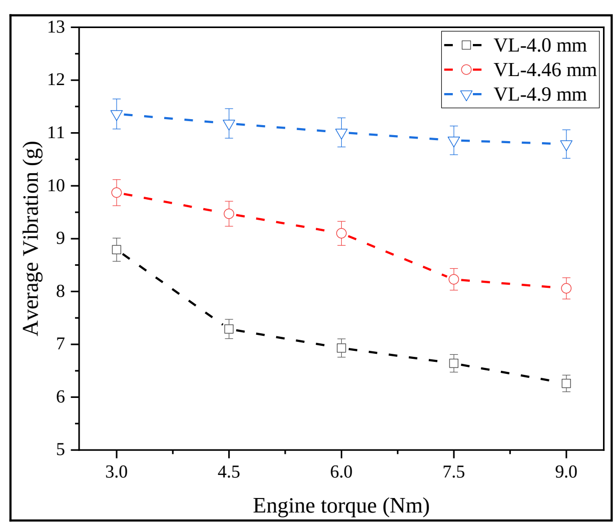

Fig. 10. The effect of valve lift variation on average vibration under different engine load conditions.

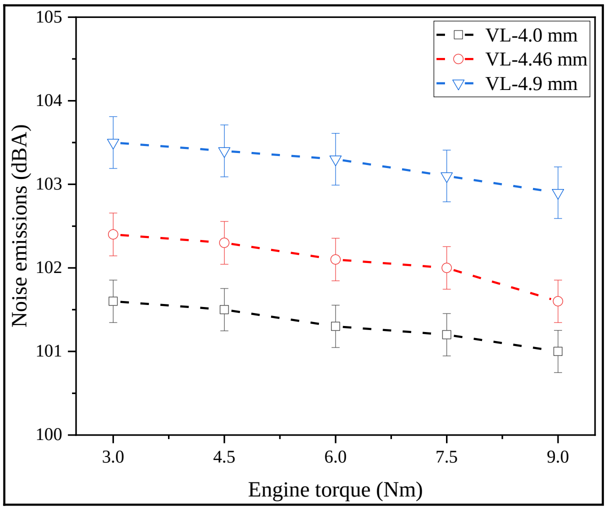

Fig. 11. The effect of valve lift variation on noise emissions under different engine load conditions.

Fig. 11 illustrates the impact of varying valve lift amounts on noise emissions under different engine load conditions. Based on the findings depicted in the figure, an increase in engine load has demonstrated a notable inverse relationship with noise emissions across all valve lifts. Although there was a decreasing trend in noise levels with increasing engine load, there was slight a difference of 0.8 dBA between the noise emissions at 3 Nm engine load and 9 Nm engine load for the original engine camshaft. Similarly, for the cam profile with a valve lift of 4.46 mm, this difference was 0.5 dBA, while for the cam profile with a valve lift of 4.9 mm, the difference was 0.6 dBA. The reason for this is that under high loads, the occurrence of stable combustion phases leads to a reduction in engine mechanical vibrations, which has a positive impact on noise emissions. At low loads, a delayed start of combustion tends to lead to knock combustion, resulting in higher vibrations and noise emissions. With an increase in load, combustion becomes more stable, leading to a relatively decrease in both vibration and noise emissions.

The lowest levels of noise emissions were observed under 9 Nm engine torque conditions for all valve lifts, whereas the highest levels were recorded under 3 Nm engine torque conditions. On the other hand, the variation in cam profile has had a significant impact on engine noise emission values. The cam profile with a valve lift of 4.9 mm has resulted in approximately a 1% increase in noise emissions compared to the original valve lift amount of 4.46 mm. Conversely, the cam profile with a valve lift of 4.0 mm has led to approximately a 0.8% decrease in noise emissions compared to the original valve lift amount of 4.46 mm. While an increase in engine load did not exhibit a significant change in engine noise emissions, the valve lift amount did have some impact. The decrease in vibration values can be attributed to the reduction in engine noise emissions. Additionally, under high load conditions, a more stable combustion phase might have contributed to a slight decrease in noise levels.

3. Conclusions

In this study, the design of cam profiles with different valve opening amounts for a common rail dual-fuel engine was carried out using the circular spring curve method, fitted with a Fourier series, and subsequently manufactured. Afterward, the vibration and noise emission effects generated by the manufactured cam profiles on the engine were experimentally investigated. The experiments were conducted at five different engine loads (3, 4.5, 6, 7.5, and 9 Nm) and a constant engine speed of 1850 rpm. The cam profiles used in the study had different valve lift amounts of 4.0 mm, 4.46 mm, and 4.9 mm.

The results regarding the effect of cam profiles with different valve lift amounts on average vibration and noise emission can be summarized as follows:

•The cam profiles designed using the circular spring curve and fitted with the Fourier series exhibited closely matched values.

•An increase in valve lift results in a significant increase in acceleration and leap values.

•Compared to the original valve lift amount of the engine, a reduction in valve lift amount has led to a 20% decrease in average vibration. On the other hand, an increase in valve lift amount has caused an approximately 24% increase in average vibration.

•Due to the occurrence of a less stable combustion phase under low load conditions, higher vibration values are observed, whereas an increase in engine load results in the realization of a more stable combustion characteristic, leading to lower vibration values.

•The variation in engine load had no significant impact on noise emission. However, the effect of cam profile modification on average emissions was quite evident. The cam profile with a low valve lift amount exhibited the lowest noise emission value, while the cam profile with a high valve lift amount showed the highest noise emission value.

•Overall, these results demonstrate that the valve lift amount is a determining factor in the average vibration and noise performance of the engine. Lower valve lift amounts result in reduced average vibration and noise emissions, while higher valve lift amounts amplify these effects.

In future studies, the effects of alternative gas fuels such as methane and hydrogen can be experimentally investigated under dual-fuel mode to reduce vibration and noise emissions of diesel engines.

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Nomenclature

θ	Valve opening duration
θ_1	Maximum angle of the second circular arc

θ_2	Maximum angle of the first circular arc
h_2	Maximum valve lift
r	Base circle radius
CAD	Crank angle degree
CNC	Computer Numerical Control
CO	Carbon monoxide
dBA	Decibels A-weighted
DI	Direct injection
HC	Hydrocarbon
HCCI	Homogeneous charge compression ignition
HDPI	High-pressure direct injection
HRC	Rockwell Hardness C scale
ICE	Internal combustion engine
LPG	Liquefied petroleum gas
NO_x	Nitrogen oxides
SI	Spark ignition
VL	Valve lift

Conflict of Interest Statement

The authors declare that there is no conflict of interest in the study.

CRediT Author Statement

Halil Erdi Gülcan: Review, Conceptualization, Data curation, Formal analysis, Writing-original draft-editing, Validation, **Nurullah Gültekin:** Review, Conceptualization, Writing-original draft, Validation, **Murat Ciniviz:** Review**,** Supervision, and Funding acquisition.

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