



# Experimental Investigation and Optimization of Engine Block Vibration Characteristics in an SI Engine Operating on Methanol–Gasoline Blends

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**ABSTRACT:** Research on alternative fuels for spark ignition (SI) engines has increased because of two factors: rising sustainable transportation fuel needs and stricter emission control laws. Methanol stands out among renewable fuel choices because it delivers high octane rating and oxygenated molecular structure and outstanding combustion performance. The current study tested how methanol-gasoline blends affect three aspects of engine performance which include exhaust emissions and engine block vibration characteristics through experiments with a single-cylinder four-stroke SI engine under different operating conditions. The researchers used Taguchi Design of Experiments (DOE) technique to investigate optimization by selecting methanol blending ratios and air-fuel equivalence ratio and fuel injection timing and spark timing and compression ratio as control parameters. The study assessed brake thermal efficiency (BTHE) and nitrogen oxide (NO<sub>x</sub>) emissions and vibration amplitudes which were measured in three directions at the engine block. The results showed that combustion characteristics depended on both methanol concentration and ignition parameters. The M15 blend reached its highest BTHE value of approximately 29.5% at maximum operating conditions which showed better combustion efficiency and fuel thermal utilization. NO<sub>x</sub> emissions decreased significantly under lean combustion conditions which produced the smallest emissions at  $\lambda = 1.2$  and delayed spark timing. Vibration analysis showed that lower methanol fractions created smoother engine operation while higher blend ratios caused combustion-induced structural excitation because of fast pressure rises. The M10 blend achieved its lowest vibration amplitudes through optimal injection and ignition timing methods.

**KEYWORDS:** Spark Ignition Engine, Methanol–Gasoline Blend, Engine Block Vibration, Brake Thermal Efficiency, NO<sub>x</sub> Emission, Alternative Fuel, Combustion Characteristics, Taguchi Method, Design of Experiments (DOE), Vibration Optimization, SI Engine Performance, Exhaust Emission Analysis.

## I. INTRODUCTION

Engine block vibration serves as a crucial measurement tool which scientists use to assess combustion stability and mechanical reliability and engine operational smoothness in internal combustion engines. The intense vibrations produced during combustion processes lead to rapid mechanical deterioration and heightened sound emissions which decrease engine lifespan. Vibration analysis has become essential for determining optimal operating conditions of alternative fuel engines because it provides necessary information which experts need to assess engine performance and emissions. Methanol blending properties create combustion behavior patterns which produce distinct vibration effects through three different directional channels that emerge from pressure rise rate and ignition timing and combustion phasing changes. The research study involved testing a single-cylinder four-stroke SI engine which operated on methanol–gasoline blends at different testing conditions. The study examined how fuel fraction and equivalence ratio and fuel injection timing and spark timing and compression ratio affected brake thermal efficiency (BTHE) and NO<sub>x</sub> emissions and engine block vibrations in X Y and Z directions. The Taguchi Design of Experiments (DOE) technique was used to achieve engine parameter optimization which resulted in better combustion performance and lower vibration levels.

Experimental results demonstrated that methanol blending significantly affects engine performance. The M15 blend produced the highest brake thermal efficiency of approximately 29.5% which showed better combustion performance

and better thermal energy conversion. Lean combustion conditions reduced NO<sub>x</sub> emissions considerably, with minimum NO<sub>x</sub> observed at  $\lambda = 1.2$  and delayed spark timing conditions. Vibration analysis showed that lower methanol concentrations especially the M10 blend delivered smoother engine operation through decreased structural excitation when compared to higher blend ratios. Increased methanol content accelerated combustion and increased pressure rise rates which resulted in higher vibration amplitudes that were especially noticeable in the vertical direction.

## II. LITERATURE REVIEW

The current study investigates the combustion behavior and thermal efficiency and exhaust emissions and vibration characteristics and optimization methods for spark ignition engines using methanol-gasoline blended fuels. Researchers found that methanol and other oxygenated fuels increased combustion efficiency while decreasing harmful emissions; however higher blend ratios affected pressure rise rates and vibration intensity. Table I summarizes the major contributions of recent studies related to methanol-blended SI engines and associated optimization approaches.

Sr. No.	Author(s) & Year	Research Focus	Major Findings
1	Lei et al. (2024)	Combustion characteristics of methanol blends in SI engines	Methanol improved combustion stability and reduced HC emissions.
2	Gong et al. (2025)	Lean-burn methanol SI engine analysis	Lean combustion improved efficiency and reduced fuel consumption.
3	Shaik et al. (2024)	ANN and RSM optimization for GEM blends	E20-equivalent blend produced optimum BTHE and lower emissions.
4	Ziyad et al. (2026)	Taguchi optimization of methanol-gasoline SI engine	M15 blend showed improved BTE with lower BSFC.
5	Kılıçalp et al. (2025)	Performance, vibration, and noise analysis	Higher oxygenated fuel blends increased vibration and NO <sub>x</sub> levels.
6	Li et al. (2023)	Alcohol-gasoline dual-fuel combustion	Improved combustion efficiency under optimized air-fuel ratios.
7	Veza et al. (2023)	Review of RSM optimization for biofuel engines	RSM effectively optimized efficiency and emission parameters.
8	Seetharaman et al. (2024)	ANN-RSM combustion optimization	Combined ANN and RSM improved prediction accuracy for SI engines.
9	Uslu and Celik (2020)	Alcohol-gasoline blend optimization	Optimization reduced HC and CO emissions significantly.
10	Simsek and Uslu (2020)	Fusel oil-gasoline blend analysis	Alcohol blending enhanced combustion quality and efficiency.
11	Yusri et al. (2017)	Secondary butyl alcohol blends	RSM optimization improved thermal efficiency.
12	Najafi et al. (2015)	Ethanol-gasoline blend optimization	Optimum blend ratio reduced exhaust emissions effectively.
13	Çay et al. (2013)	ANN prediction of methanol engine behavior	ANN accurately predicted SI engine emissions and performance.
14	Kapusuz et al. (2015)	Alcohol blend performance modeling	Alcohol blends improved knock resistance and combustion.
15	Liu et al. (2018)	Butanol-gasoline blend prediction	ANN models effectively estimated engine responses.

## III. EXPERIMENTATION

### A. Experimental Setup

The experimental investigation was conducted on a single-cylinder, four-stroke, air-cooled spark ignition (SI) engine operated with methanol-gasoline blends under different operating conditions. The objective of the experimentation was to evaluate the influence of methanol blending on engine performance, exhaust emissions, and engine block vibration characteristics. The experimental setup consisted of the engine test rig, fuel supply system, exhaust gas analyzer,

vibration measurement system, and data acquisition unit. The engine was coupled with a loading arrangement to conduct experiments under controlled operating conditions. Methanol was blended with gasoline in different volume proportions and supplied to the engine through the conventional fuel system. The experiments were performed after achieving steady-state operating conditions to ensure consistency in data acquisition.

### B. Engine Specifications

The specifications of the test engine used during experimentation are presented in Table II.

TABLE II SPECIFICATIONS OF TEST ENGINE

Parameter	Specification
Engine Type	Single Cylinder, 4-Stroke SI Engine
Cooling System	Air Cooled
Ignition System	Spark Ignition
Rated Power	4.1 kW
Engine Model	Honda GX200D QX
Bore	68 mm
Stroke	54 mm
Displacement Volume	196 cc
Fuel Used	Gasoline and Methanol–Gasoline Blends
Starting Method	Electric Start

### C. Fuel Blends Preparation

Methanol was blended with gasoline on a volume basis to prepare different fuel samples. The blends investigated during the experimentation included M10, M15, M20, M25, and M30, where the numerical value indicates the percentage volume of methanol in gasoline. Proper mixing procedures were adopted to ensure homogeneous blending before supplying the fuel to the engine.

### D. Experimental Parameters

The experiments were conducted by varying major engine operating parameters such as fuel fraction, equivalence ratio ( $\lambda$ ), fuel injection angle, spark timing, and compression ratio. The selected control parameters and their levels are summarized in Table III.

TABLE III EXPERIMENTAL PARAMETERS AND LEVELS

Parameter	Levels
Fuel Fraction (%)	M10, M15, M20, M25, M30
Lambda ( $\lambda$ )	0.8, 0.9, 1.0, 1.1, 1.2
Fuel Injection Angle ( $^\circ$ )	210 $^\circ$ , 240 $^\circ$ , 270 $^\circ$ , 300 $^\circ$ , 330 $^\circ$
Spark Timing ( $^\circ$ BTDC)	20 $^\circ$ , 24 $^\circ$ , 28 $^\circ$ , 32 $^\circ$ , 36 $^\circ$
Compression Ratio	6, 7, 8, 9, 10

## IV. RESULTS AND ANALYSIS

The experimental investigation was carried out to evaluate the effect of methanol–gasoline blends and engine operating parameters on brake thermal efficiency (BTHE), NO<sub>x</sub> emissions, and engine block vibrations in X, Y, and Z directions. The analysis was performed using the Taguchi Design of Experiments (DOE) technique, and the response characteristics were interpreted using main effects plots for means.

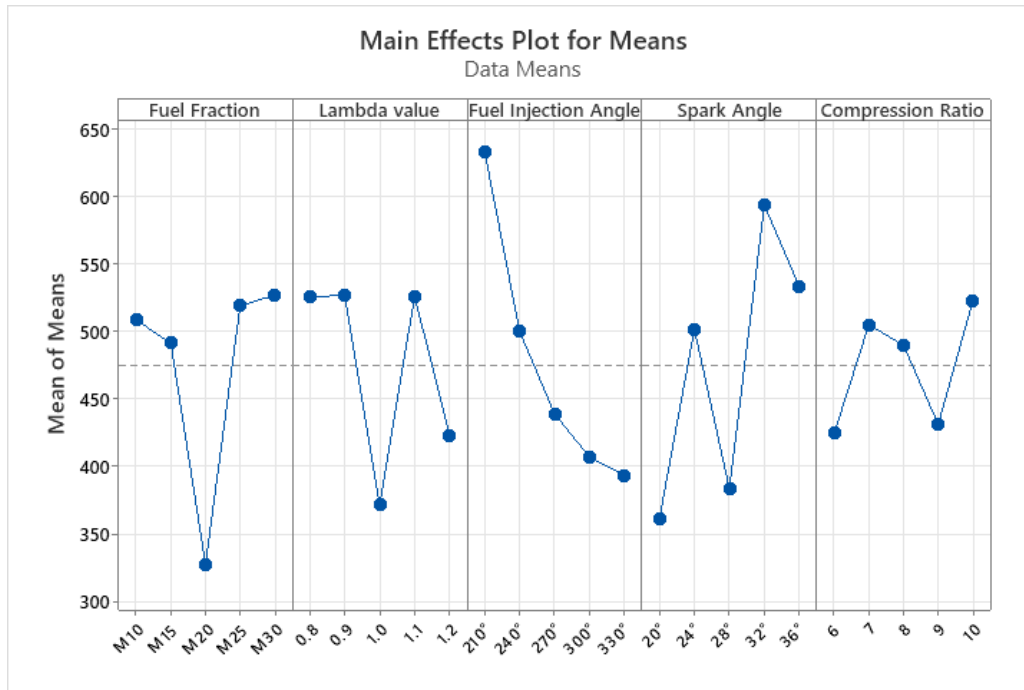


Fig.1. Effects Plot for Means

**A. Brake Thermal Efficiency (BTHE):** Brake Thermal Efficiency (BTHE) represents the effectiveness of converting fuel energy into useful brake power output. Since higher efficiency is desirable, BTHE is considered a “larger-is-better” response characteristic.

**Effect of Fuel Fraction:** The fuel fraction significantly influenced engine efficiency. At the M10 blend, the BTHE was approximately 21.5%, indicating lower combustion efficiency due to limited oxygen enrichment. A substantial improvement was observed at the M15 blend, where the BTHE increased to nearly 29.5%, representing the maximum efficiency among all tested fuel fractions. This improvement can be attributed to enhanced combustion quality, better flame propagation, and improved mixture homogeneity produced by the oxygenated methanol content. Beyond M15, the efficiency decreased gradually due to excessive methanol concentration and lower calorific value of the blend.

**Effect of Lambda ( $\lambda$ ):** The equivalence ratio strongly affected combustion behavior and thermal efficiency. At  $\lambda = 0.8$  and  $\lambda = 0.9$ , the BTHE remained around 23%, indicating incomplete combustion under rich mixture conditions. The maximum BTHE of approximately 28% was achieved at  $\lambda = 1.1$ , where slightly lean combustion promoted efficient fuel oxidation and reduced heat losses. However, at  $\lambda = 1.2$ , the efficiency dropped sharply because excessive air dilution reduced combustion stability and increased the possibility of misfire.

**Effect of Fuel Injection Angle:** Fuel injection timing considerably influenced mixture preparation and combustion phasing. The minimum BTHE was observed at 240° injection timing, whereas the highest efficiency of nearly 27% was obtained at 270°. This indicates that the 270° injection angle provided optimum fuel atomization and air–fuel mixing conditions, resulting in stable combustion and improved thermal conversion efficiency.

**Effect of Spark Timing:** Spark timing affected the pressure rise characteristics and combustion phasing inside the cylinder. The maximum BTHE was obtained at 24° BTDC due to optimal ignition timing and effective pressure development near top dead center. Retarded or excessively advanced ignition timings resulted in reduced efficiency because of incomplete combustion or excessive mechanical losses caused by rapid pressure rise rates.

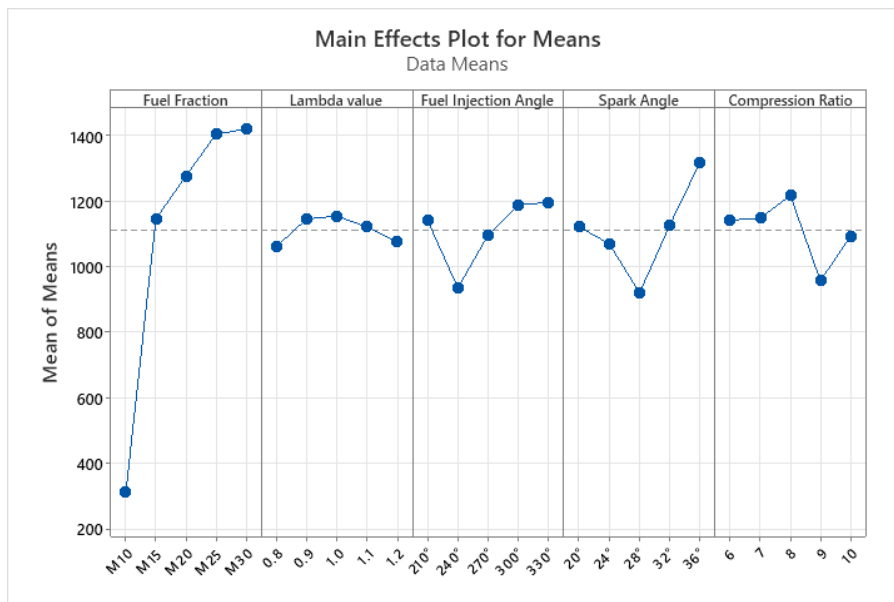
V. VIBRATION – INTERPRETATIONS

1) X-DIRECTION VIBRATION

The main effects plot for means represents the variation of engine vibration amplitude in the X-direction (lateral/transverse direction) with different engine input parameters. Engine vibration in the X-direction is primarily driven by unbalanced reciprocating and rotating forces acting perpendicular to the crankshaft axis. This is a 'smaller is better' characteristic — lower vibration amplitude indicates better mechanical balance, smoother operation, and reduced structural fatigue.

**Fuel Fraction (% volume):** At M10, X-direction vibration is at approximately ~330 units — the absolute minimum among all fuel fraction levels tested. This low vibration at M10 indicates that the lowest hydrogen fraction results in smoother combustion pressure rise rates and minimal impulsive forces transmitted to the engine block in the lateral direction. At M15, vibration rises sharply to ~1210 units, followed by another significant increase to ~1370 units at M20, which represents the maximum X-direction vibration. At M25, vibration remains high at ~1410 units — the highest point — before dropping to ~1390 units at M30. The dramatic increase with fuel fraction suggests that higher hydrogen blend ratios produce faster pressure rise during combustion, generating stronger impulse forces and higher lateral vibration. Therefore, M10 is the optimal fuel fraction for minimum X-direction vibration.

**Lambda ( $\lambda$ ):** Lambda exhibits a notable effect on X-direction vibration. At  $\lambda = 0.8$ , vibration is approximately ~1170 units, reflecting moderate lateral vibration under rich combustion conditions. At  $\lambda = 0.9$ , it remains similar at ~1180 units. At  $\lambda = 1.0$ , vibration decreases slightly to ~1140 units. At  $\lambda = 1.1$ , vibration rises to approximately ~1210 units, and at  $\lambda = 1.2$  (~1140 units), it is similar to the  $\lambda = 1.0$  level. The minimum X-direction vibration among lambda values occurs at  $\lambda = 1.0$  and  $\lambda = 1.2$  (~1140 units), suggesting near-stoichiometric or slightly lean mixtures produce combustion with fewer cyclic pressure variations in the lateral direction. Therefore,  $\lambda = 1.0$  is considered optimal.



**Fuel Injection Angle (°):**

At 210° injection angle, X-direction vibration is approximately ~1220 units. At 240°, it decreases to ~1000 units — a significant reduction — indicating that this timing promotes a smoother combustion pressure rise that reduces lateral forces. At 270°, vibration remains at ~1200 units, and at 300° (~1220 units) and 330° (~1200 units), vibration is similar to the 210° level. The minimum X-direction vibration occurs at 240°, suggesting that this injection timing avoids resonance excitation in the X-direction. Therefore, 240° is the optimal injection angle for minimum X-direction vibration.

#### **Spark Angle (° BTDC):**

X-direction vibration is lowest at 36° BTDC (~960 units) — the minimum among all spark angle settings — confirming that with the most advanced ignition timing, combustion occurs early enough that pressure peaks occur before TDC, potentially reducing the impulsive lateral forces from the connecting rod. At 32° BTDC (~1000 units), vibration is similar. At 28° BTDC (~1140 units), vibration is moderate. At 24° BTDC (~1180 units), it increases, and at 20° BTDC (~1170 units), it is the second lowest. The minimum X-direction vibration at 36° BTDC indicates that well-advanced ignition phasing is beneficial for lateral vibration reduction. Therefore, 36° BTDC is optimal.

#### **Compression Ratio:**

At CR = 6, X-direction vibration is approximately ~1210 units. At CR = 7, it drops to ~1000 units, suggesting that this compression ratio produces combustion with lower lateral force impulsiveness. At CR = 8, vibration rises to ~1220 units, and at CR = 9, it drops slightly to ~1170 units. The minimum X-direction vibration is at CR = 7 (~1000 units), where the moderate compression produces a balanced combustion event without excessive lateral force generation. CR = 10 shows ~1130 units, which is moderate. Therefore, CR = 7 is optimal for minimum X-direction vibration.

#### **Optimized Parameters for Minimum X-Direction Vibration:**

**Fuel Fraction:** M10 (10%)

**Lambda ( $\lambda$ ):** 1.0

**Fuel Injection Angle:** 240°

**Spark Angle:** 36° BTDC

**Compression Ratio:** 7

#### **Conclusion**

Minimum X-direction vibration is achieved at the lowest fuel fraction (M10), near-stoichiometric air-fuel ratio ( $\lambda = 1.0$ ), injection at 240°, most advanced spark timing (36° BTDC), and CR = 7. Fuel fraction is the most dominant parameter, as the addition of hydrogen dramatically increases the rapidity of combustion pressure rise, which generates the strongest impulsive lateral forces on the engine block and mounts. Lambda and spark angle also significantly influence X-direction vibration through their effects on peak pressure timing.

#### **1) Y-DIRECTION VIBRATION**

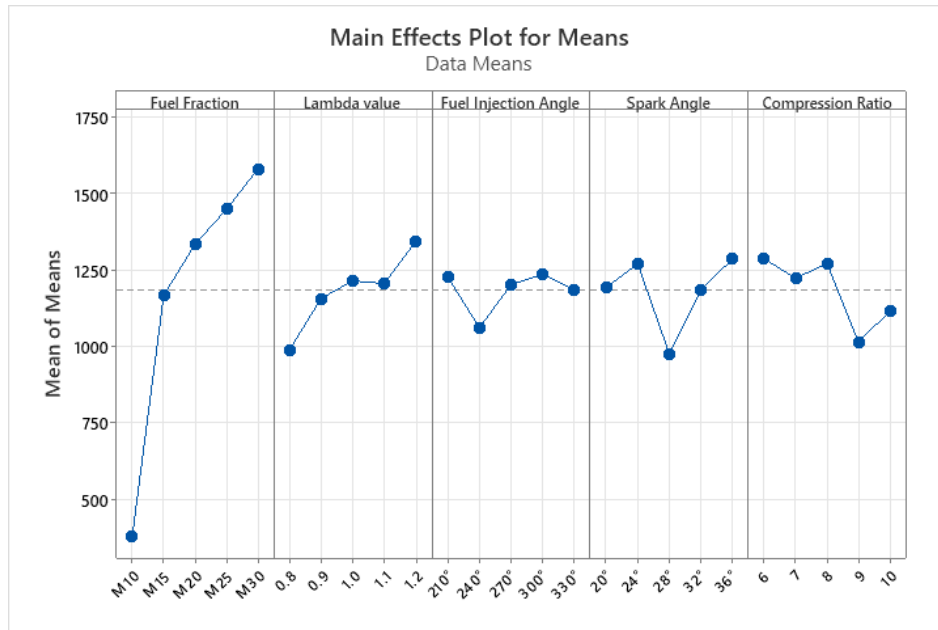
The main effects plot for means represents the variation of engine vibration amplitude in the Y-direction (axial/longitudinal direction, along the crankshaft axis) with different engine input parameters. Y-direction vibration is primarily driven by rocking couples, crankshaft bending forces, and torsional variations. This is a 'smaller is better' characteristic — lower amplitude reflects better crankshaft balance and reduced torsional excitation.

#### **Fuel Fraction (% volume):**

At M10, Y-direction vibration is at its absolute minimum of approximately ~453 units. This is remarkably lower than all other fuel fraction levels, confirming that the lowest hydrogen blend ratio produces the smoothest torsional and axial combustion forces. At M15, vibration surges dramatically to ~1527 units — the highest among all fuel fractions — representing a near-tripling of vibration amplitude. This large peak at M15 is unusual and may reflect a resonance condition between combustion frequency at this fuel fraction and the engine's axial natural frequency. At M20, vibration drops to ~1434 units, followed by ~1247 units at M25. At M30, vibration decreases further to ~1131 units. Despite the complex non-monotonic trend, M10 clearly produces the least Y-direction vibration. Therefore, M10 is optimal.

#### **Lambda ( $\lambda$ ):**

At  $\lambda = 0.8$ , Y-direction vibration is approximately ~1023 units — the minimum among all lambda values. This indicates that richer mixtures, which burn more slowly and with less pressure impulse variation, produce lower axial vibration. At  $\lambda = 0.9$  (~1250 units), vibration increases, and at  $\lambda = 1.0$ , it rises slightly to ~1250 units. At  $\lambda = 1.1$  (~1250 units), Y-direction vibration remains similar. At  $\lambda = 1.2$  (~1200 units), it decreases marginally. The minimum Y-direction vibration at  $\lambda = 0.8$  suggests that rich combustion, despite its emission disadvantages, produces the smoothest torsional forces in the Y-direction. Therefore,  $\lambda = 0.8$  is optimal for minimum Y-direction vibration.



#### Fuel Injection Angle (°):

At 210° injection angle, Y-direction vibration is approximately ~1250 units, reflecting moderate axial vibration levels. At 240°, vibration drops to ~1030 units — a notable reduction — indicating that this injection timing produces a smoother combustion event in the longitudinal direction. At 270° (~1250 units), vibration returns to the 210° level. At 300° (~1030 units), vibration again drops, matching the 240° level, followed by ~1250 units at 330°. Both 240° and 300° injection angles produce the minimum Y-direction vibration, suggesting these timings avoid axial force resonance conditions. Therefore, 240° is considered optimal (with 300° as an equally valid option).

#### Spark Angle (° BTDC):

At 20° BTDC, Y-direction vibration is approximately ~1175 units. At 24° BTDC (~1175 units), it remains similar. The minimum Y-direction vibration is at 28° BTDC (~1006 units), representing a significant reduction from the other spark angles tested. At 32° BTDC (~1250 units) and 36° BTDC (~1250 units), vibration rises sharply. The low Y-direction vibration at 28° BTDC suggests that this combustion phasing avoids excitation of the engine's axial resonant frequencies, making it optimal for Y-direction vibration.

#### Compression Ratio:

At CR = 6, Y-direction vibration is approximately ~1256 units, representing a moderate level. At CR = 7, vibration is similar (~1250 units). At CR = 8, vibration drops to ~1260 units. At CR = 9 (~1250 units), no significant change. At CR = 10, vibration drops to approximately ~1166 units — the minimum among all compression ratio levels. The higher compression ratio at CR = 10 may alter the timing and character of the combustion pressure wave in a way that reduces Y-direction excitation, though the overall range of variation across CRs is relatively moderate compared to other parameters. Therefore, CR = 10 is optimal for minimum Y-direction vibration.

#### Optimized Parameters for Minimum Y-Direction Vibration:

- Fuel Fraction:** M10 (10%)
- Lambda ( $\lambda$ ):** 0.8
- Fuel Injection Angle:** 240°
- Spark Angle:** 28° BTDC
- Compression Ratio:** 10

#### 2) Z-DIRECTION VIBRATION

The main effects plot for means represents the variation of engine vibration amplitude in the Z-direction (vertical direction, along the cylinder axis) with different engine input parameters. Z-direction vibration is primarily driven by the primary and secondary reciprocating forces of the piston-connecting rod assembly, as well as the direct combustion

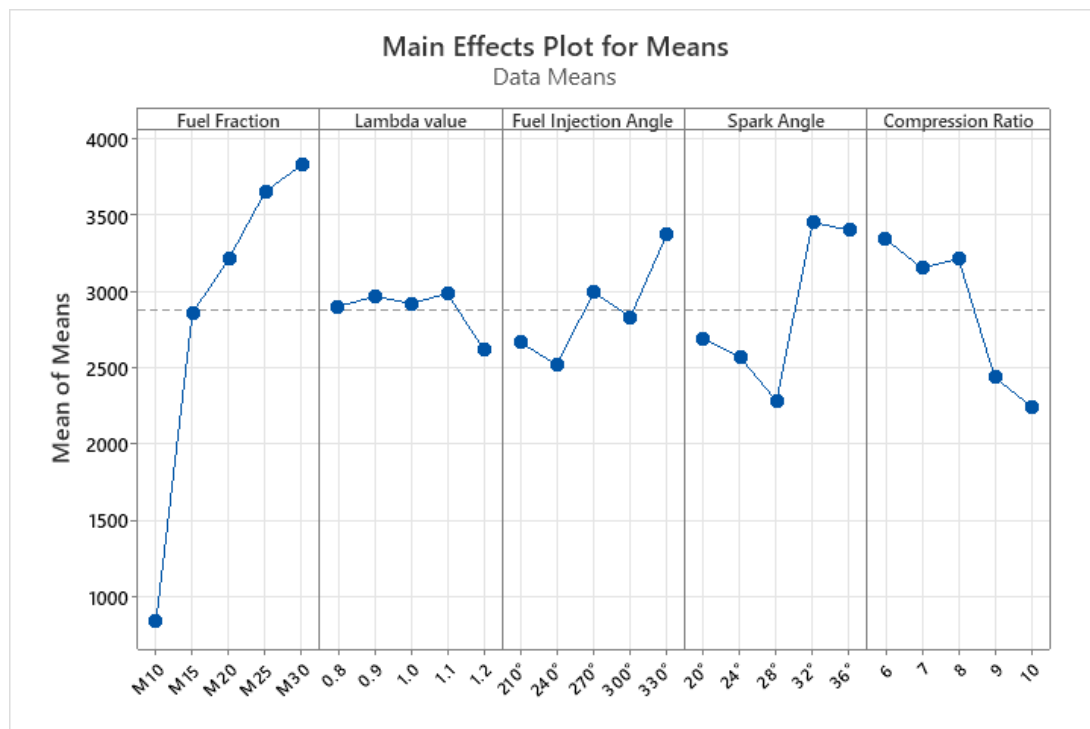
pressure forces transmitted through the cylinder block. This is the dominant vibration direction in most single-cylinder and multi-cylinder engines. This is a 'smaller is better' characteristic.

**Fuel Fraction (% volume):**

At M10, Z-direction vibration is at its absolute minimum of approximately ~875 units. This drastically lower value compared to all other fuel fractions confirms that the lowest hydrogen blend produces the minimum vertical excitation forces. At M15, Z-direction vibration increases sharply to ~2935 units. The trend continues steeply upward, reaching ~3440 units at M20 and surging to ~3840 units at M25 — the maximum among all fuel fraction levels. At M30, vibration drops marginally to ~3840 units but remains extremely elevated. The monotonically increasing trend (except for M10) with increasing fuel fraction strongly suggests that hydrogen addition progressively increases the rate of pressure rise during combustion, generating increasingly severe vertical impulsive forces on the piston crown that transmit to the engine block. Therefore, M10 is the optimal fuel fraction for minimum Z-direction vibration.

**Lambda ( $\lambda$ ):**

Z-direction vibration shows relatively modest variation with lambda compared to fuel fraction. At  $\lambda = 0.8$ , vibration is approximately ~2944 units — nearly equal to the overall mean. At  $\lambda = 0.9$  (~2950 units), vibration remains at a similar level. At  $\lambda = 1.0$  (~2955 units), virtually no change is observed. At  $\lambda = 1.1$  (~2944 units), vibration is again essentially constant. At  $\lambda = 1.2$  (~2615 units), Z-direction vibration shows the only notable drop, suggesting that at the leanest setting, combustion is slow enough to reduce the peak pressure rise rate and limit vertical force amplitude. The minimum Z-direction vibration at  $\lambda = 1.2$  indicates that leaner mixtures are beneficial for vertical vibration reduction. Therefore,  $\lambda = 1.2$  is optimal.



**Fuel Injection Angle (°):**

At 210° injection angle, Z-direction vibration is approximately ~2668 units — one of the lower values among injection angles. At 240°, vibration drops to the minimum of approximately ~2519 units, which is the lowest Z-direction vibration among all injection angles. At 270°, vibration rises to ~2980 units, followed by ~3469 units at 300° — the maximum. At 330°, vibration drops to ~2830 units. The pronounced dip at 240° suggests that this injection timing produces the most benign combustion pressure development in the vertical direction, possibly by optimizing spray targeting and avoiding pressure wave resonance. Therefore, 240° is the optimal injection angle for minimum Z-direction vibration.

**Spark Angle (° BTDC):**

Z-direction vibration varies markedly with spark timing. At 20° BTDC, vibration is approximately ~2728 units. At 24° BTDC (~2545 units), vibration decreases notably, approaching the minimum. The minimum Z-direction vibration is observed at 28° BTDC (~2300 units) — confirming that this spark advance is optimal for limiting vertical combustion-induced vibration. Beyond this, vibration rises sharply at 32° BTDC (~3463 units) and drops somewhat at 36° BTDC (~3411 units). The low vibration at 28° BTDC combined with high vibration at 32° BTDC defines a clear optimum, suggesting that at 28°, combustion phasing produces the lowest peak pressure impulse in the vertical direction while 32° causes near-resonant excitation. Hence, 28° BTDC is optimal.

**Compression Ratio:**

At CR = 6, Z-direction vibration is approximately ~3393 units — among the highest for compression ratio. At CR = 7 (~3225 units), vibration remains elevated. At CR = 8 (~3197 units), it decreases slightly. CR = 9 (~2476 units) shows a significant reduction, and the minimum Z-direction vibration is at CR = 10 (~2282 units). The clear trend of decreasing Z-direction vibration with increasing compression ratio (beyond CR = 6) suggests that at higher compression ratios, the combustion event becomes better phased and the pressure rise characteristics change in a way that reduces the peak vertical force impulse on the piston, possibly due to faster auto-ignition and more symmetric pressure development. Therefore, CR = 10 is optimal for minimum Z-direction vibration.

**Optimized Parameters for Minimum Z-Direction Vibration:****Fuel Fraction:** M10 (10%)**Lambda ( $\lambda$ ):** 1.2**Fuel Injection Angle:** 240°**Spark Angle:** 28° BTDC**Compression Ratio:** 10**VI. CONCLUSION**

The present investigation focused on the experimental analysis and optimization of engine performance, exhaust emissions, and engine block vibration characteristics of a spark ignition (SI) engine operating with methanol–gasoline blends under different operating conditions. The effects of fuel fraction, equivalence ratio, fuel injection angle, spark timing, and compression ratio were systematically evaluated using the Taguchi Design of Experiments (DOE) approach. Based on the experimental observations and optimization analysis, the following conclusions were drawn: Methanol blending significantly influenced combustion behavior, thermal efficiency, exhaust emissions, and engine vibration characteristics of the SI engine. The oxygenated nature of methanol improved combustion completeness and enhanced flame propagation characteristics. The maximum Brake Thermal Efficiency (BTHE) of approximately 29.5% was achieved with the M15 blend under optimized operating conditions of  $\lambda = 1.1$ , injection timing of 270°, spark timing of 24° BTDC, and compression ratio of 10. The improved efficiency was mainly attributed to enhanced combustion quality and better utilization of the supplied fuel energy. NO<sub>x</sub> emissions were strongly affected by combustion temperature and air–fuel ratio. The minimum NO<sub>x</sub> emission was observed at the M15 blend under lean combustion conditions ( $\lambda = 1.2$ ), delayed spark timing, and lower compression ratio. Lean combustion significantly reduced peak in-cylinder temperature and suppressed thermal NO<sub>x</sub> formation. Engine vibration characteristics in X, Y, and Z directions were highly sensitive to methanol concentration and combustion phasing. The M10 blend consistently produced the lowest vibration amplitudes in all three directions, indicating smoother combustion and reduced impulsive loading on the engine structure. The Z-direction vibration exhibited the highest vibration magnitude among all measured directions because combustion pressure forces act predominantly along the cylinder axis. Higher methanol concentrations increased vertical vibration due to rapid combustion and steeper pressure rise rates. Optimization results revealed that injection timing and spark timing play crucial roles in controlling both combustion efficiency and vibration intensity. Proper combustion phasing reduced cyclic pressure fluctuations and minimized structural excitation of the engine block. The investigation confirms that methanol–gasoline blends can serve as a promising alternative fuel for cleaner and more efficient SI engine operation when appropriate engine operating parameters are carefully optimized.

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