Study on Cylinder-to-Cylinder Nonuniformity of Heavy-Duty Spark-Ignited Methanol Engine under Cold Start Idle Mode

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Abstract. The cylinder-to-cylinder nonuniformity problem of a V8 heavy duty methanol engine under cold start idle mode is investigated in this paper. A data acquisition program for collecting the original signal of the engine speed was designed using Labview graphical programming software. Combined with NI data acquisition equipment, the original signals of the crankshaft and camshaft speeds were collected. By calculating the instantaneous speeds of each cylinder's power stroke, the speed fluctuation and nonuniformity degree of each cylinder were determined. Combining the intake mass data of each cylinder, the nonuniformity of each cylinder was analyzed based on this information. The calculation results indicate that there are certain differences in the power stroke capabilities of each cylinder under idle conditions, and the nonuniformity of each cylinder is caused by variations in intake mass.

Key words: Methanol Engine ; cold start; idle; speed; cylinder nonuniformity.

1. Introduction

Diesel engines have long been the primary power source in the marine industry due to their high efficiency and reliability[1]. To achieve the dual carbon goals and enhance energy security, reducing pollutant emissions and petroleum consumption, there is an urgent need to develop green alternative fuels. Methanol, as a clean, efficient, and low-carbon liquid fuel, has the advantages of being in liquid form at room temperature and atmospheric pressure, making it easy for transportation and storage[2]. At the same time, both the production capacity and output of methanol in China rank first in the world[3,4]. The research on methanol has gained increasing attention in the industry and holds the potential to become a new alternative energy source to replace diesel.

However, In the actual usage process, the differences in intake air and fuel injection quantity among cylinders, as well as various factors such as mechanical wear of each cylinder, can lead to inconsistent working conditions of the cylinders. This can result in fluctuations in the crankshaft speed, increased engine vibration, worsened noise, reduced engine lifespan, and impact on emissions and fuel efficiency.

The unevenness among engine cylinders is largely due to the uneven combustion of the air-fuel mixture, causing fluctuation in the torque acting on the piston and consequently leading to fluctuations in the instantaneous crankshaft speed. Therefore, the instantaneous speed fluctuation curve contains rich information about the engine's working process, and the study of instantaneous speed fluctuations plays an important role in analyzing the unevenness among cylinders.

The most direct method to study the unevenness among cylinders is to analyze the actual pressure inside each cylinder. However, due to the high cost and complexity of installing cylinder pressure sensors, especially challenging in multi-cylinder engines, this method is not always feasible. On the other hand, various types of speed sensors, such as Hall-effect speed sensors, are economical, stable, and durable. Therefore, both domestically and internationally, the analysis of speed is widely used to study misfires and the unevenness among cylinders.

Jilin University's Bai Lin and Li Qiankun use ECU programs to calculate the time interval between the rising edges of adjacent teeth on the crankshaft position sensor, in order to derive the instantaneous speed of each cylinder for analyzing the unevenness among cylinders[5,6]. Wu Feng, Xu Hang, He Wenhua, and others have developed a high-precision 40MHz counter and employed a sampling method at every 0.5°CA using self-designed equipment to capture speed waveforms. They have introduced a quantitative indicator, uniformity vector T, to analyze the unevenness among cylinders for studying cylinder-to-cylinder imbalances[7]. Du Wei and Liu Fushui processed the instantaneous cylinder pressure and speed data of a V6 diesel engine under different operating conditions. They analyzed the correlation between instantaneous speed fluctuations and the unevenness among cylinders[8]. Dong Dawei, Yan Bing, Li Yumei, and others have proposed a new method for measuring the unevenness of each cylinder in a diesel engine, based on the single-cylinder cut-off method. This new approach involves calculating the peak-to-peak difference in the instantaneous crankshaft speed before and after cut-off, or the mean difference in steady speed before and after cut-off[9]. Xie Yongle and Xie Sanshan proposed using the fluctuation of instantaneous angular acceleration during the power stroke in firing order under steady conditions as an indicator to evaluate the unevenness among cylinders. They conducted quantitative analysis of the angular acceleration to diagnose the unevenness among cylinders[10].

Michael Henn and Uwe Kiencke proposed a method for diagnosing the unevenness among cylinders. They simplified the torque balance equation step by step into a reduced first-order linear model. By using Kalman filtering to estimate angular velocity, they could then estimate pressure torque to analyze the unevenness among cylinders[11]. Cavina N and Ponti F proposed a research method for detecting misfires and cylinder imbalances. They utilized the speed of the expansion stroke to calculate parameters for misfire detection and cylinder torque imbalance detection, denoted as MD. By setting a threshold value for MD, they could detect engine misfires and cylinder imbalances[12]. To protect the exhaust emission system, William B and Giorgio Rizzoni introduced a strategy for onboard diagnosis of misfires. They calculated the crankshaft angular position using a crankshaft position sensor, which allowed them to determine the torque. By analyzing the extreme samples or performing frequency domain transformations of the torque waveform, they were able to assess torque imbalance and diagnose misfires[13].

This study focuses on a V8 methanol engine and utilizes the NI CompactRIO data acquisition device. In Labview graphical programming software, a speed signal acquisition program is designed to collect the original signals of crankshaft and camshaft speeds under cold start idle conditions. By applying formulas, the instantaneous speeds of each cylinder's power stroke are calculated, and in conjunction with intake mass data, the unevenness of each cylinder is analyzed.

2. Experimental equipment

The engine used in this experiment is a V8 methanol engine, with an idle speed of 650rpm. Other technical parameters are shown in Table 2.1.

Table 2.1. Main Performance Parameters of Methanol Engine

Parameter	Indicator
Engine type	V-type 8 cylinder, supercharged and intercooled
Cylinder number	8
Bore/mm	128
Stroke/mm	140
Connecting rod length /mm	255
Displacement /L	14
Compression ratio	14
Intake vortex ratio	0.4
Combustion chamber structure	ω type
Fuel injection	Inlet injection
Rated power /KW	300
Rated speed /rpm	1500

Idle speed/rpm	650

The layout of the engine test bench setup is shown in Figure 2.

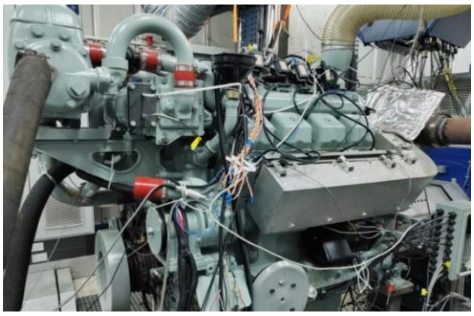

Figure 2 Engine Test Stand

The crankshaft and camshaft speed sensors used in the experiment are both Hall-effect speed sensors. The data acquisition card is an NI-9411 data acquisition card from National Instruments, and the server is an NI-CRIO-9057. Other relevant test equipment is shown in Table 2.2.

Table 2.2 Main Testing Equipment for the Test Bench

device	type
Methanol flow meter Temperature control system	FC2212L FC2440
Combustion analyzer Air flow metere	HORIBA MEXA 7100D EGR AVL FLOWSONIX Air 150
Crankshaft speed sensor	Hall type speed sensor
Cam speed sensor	Hall type speed sensor
Data acquisition card	NI-9411
Host machine	NI-CRIO-9057

3. Research Method

Due to the requirement for high precision in speed measurement, a high sampling frequency is needed. To ensure the accuracy of speed signal measurement, a 40MHz high-frequency clock sampling is employed with a sampling rate of 10us. The engine crankshaft speed sensor and camshaft speed sensor are connected to the NI-9411 data acquisition card. The NI-9057 server communicates with the host computer via Ethernet for data transmission. A program is written in LabVIEW graphical programming software to perform raw data acquisition of instantaneous crankshaft and camshaft speed signals.

The teeth of the crankshaft gear signal disc are inspected to determine the working phase of the crankshaft gear signal disc corresponding to the compression top dead center of each cylinder. Based on the firing order and tooth inspection results of the 234V8 methanol engine, the relationship between the work stroke compression top dead center of each cylinder and the phase of the crankshaft gear signal disc is determined. Calculate the instantaneous speed of each cylinder based on the rotational speed calculation formula f=nZ/60, and perform cylinder unevenness analysis by integrating the intake mass of each cylinder

4. Speed signal acquisition

4.1 Hall-effect speed sensor

The Hall effect refers to the phenomenon where applying a current to a conductor in a magnetic field, with the magnetic field direction perpendicular to the current direction, causes the electrons in the conductor to experience the Lorentz force and electric field force, resulting in a stable voltage known as the Hall voltage. In the Hall effect, the conductor is called the Hall element, and this phenomenon is known as the Hall effect. Hall-effect speed sensors are made based on this principle.

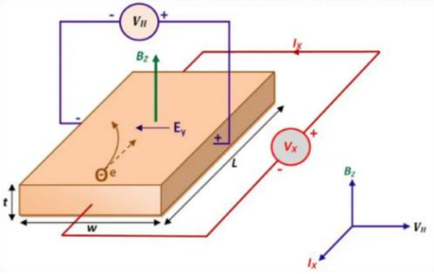

Figure 4.1 Hall Effect Principle

In this experiment, the signal gear disc used for the crankshaft speed sensor is a 60-2 tooth gear disc, where 2 indicates two missing teeth. The purpose of the missing teeth is to determine the starting working phase of the cylinder, and combined analysis with the camshaft signal can help in cylinder identification. For the camshaft speed sensor, a ferromagnetic nail is positioned at a suitable location on the camshaft gear disc. When the Hall sensor passes by this nail, the voltage of the Hall speed sensor changes. During one working cycle of the engine, the crankshaft passes through 116 teeth, generating 116 pulse signals, while the camshaft passes by the nail once, producing one pulse signal.

When a current is passed through the Hall element, as the crankshaft position sensor or camshaft position sensor gear disc rotates, the presence of gear teeth and gaps causes intermittent passage of the Hall speed sensor. This intermittent passing of gear teeth and gaps through the Hall sensor results in periodic changes in magnetic field strength, ultimately leading to variations in the induced electromotive force, thus generating an alternating voltage signal waveform related to changes in speed. The number of square wave signals corresponds to the number of teeth passed by the gear, and the frequency of the voltage signal is equal to the frequency of the speed signal variation.

The alternating voltage signal is amplified through an amplification circuit to output a square wave signal around 0V to 12V. After passing through a single-ended to differential signal converter, it is converted into a differential signal ranging from -5V to 5V. This differential signal is then transmitted to the NI-9411 data acquisition card for further signal processing.

4.2 The acquisition and analysis of raw signals

The crankshaft speed sensor and camshaft speed sensor both provide single-ended signals. In order to ensure that the output voltage of the speed sensors falls within the high and low-level reception range of the NI-9411, and considering that analog signals are susceptible to electromagnetic interference[7]. Therefore, a signal converter is connected between the crankshaft and camshaft speed sensors and the NI-9411 to convert the single-ended signals to differential signals. The high level of the differential signal is 5V, and the low level is -5V. The wiring connection is illustrated in Figure 4.2.1.

Figure 4.2.1 Speed Signal Acquisition Circuit

The high-level reception range of the NI-9411 is 300mV to 24V, within which the digital signal output is 0. The low-level reception range is -300mV to -24V, at which point the NI-9411 outputs a digital signal of 1. LabVIEW software is used to receive the signals acquired by the NI-9411 data acquisition card. The clock counting frequency on the FPGA side is set to 40MHz, and the sampling rate is set to 10us, meaning that a signal is sampled every 10us.

On the FPGA side, the FIFO memory is invoked to store data, and on the host computer, the FIFO memory is configured to transfer data from the lower computer to the host computer while storing the raw signals. The idle speed of the V8 methanol engine 234V8 is 650rpm, so the engine completes one cycle in approximately 0.185s. The raw signals from the crankshaft and camshaft speed sensors for one cycle of engine operation are shown in Figure 4.2.2.

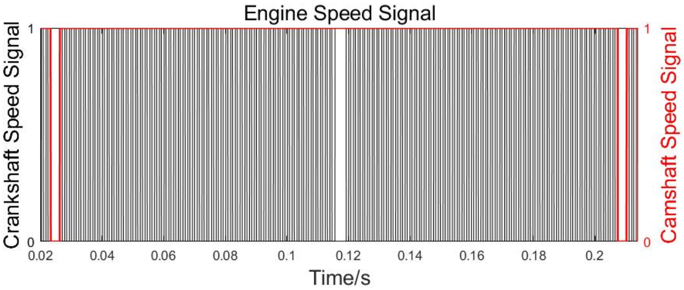

Figure 4.2.2 Crankshaft and Camshaft Raw Speed Signals

In the above Figure 4.2.2, the blank sections in the crankshaft speed signal represent the missing teeth passing through the crankshaft speed sensor, which lasts approximately three times longer than the rest of the pulse duration. From the figure, it can be observed that the camshaft speed signal aligns with the missing teeth on the crankshaft, consistent with the actual arrangement of the crankshaft and camshaft speed sensors for the 234V8 methanol engine.

5. Cylinder-to-Cylinder Nonuniformity Analysis

5.1 Tooth recognition

Define the first tooth after the missing tooth on the crankshaft gear signal disc as tooth 0, denoted as 0#. The crank angle (CA) from the missing tooth to the top dead center of exhaust stroke for cylinder 8 (8TDC) is 203°CA, and the crank angle from 8TDC to the alignment of the camshaft sensor with the camshaft is 208°CA. This is illustrated in Figure 5.1.1.

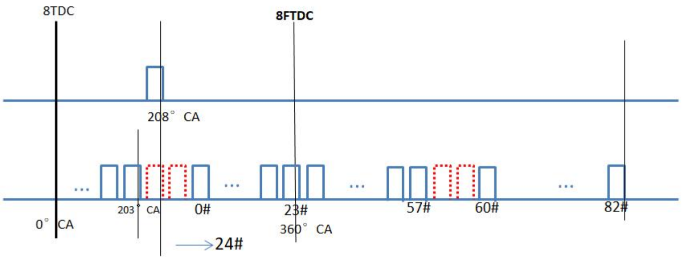

Figure 5.1.1 Engine Tooth Detection Principle

The firing order of the 234V8 methanol engine used in this experiment is 1-6-3-5-4-7-2-8. Based on the distance of 8FTDC to the missing tooth and the crank angle of a single camshaft tooth, combined with the engine's ignition angle, the tooth detection of the engine is performed. It is calculated that the compression top dead center (FTDC) for cylinder 1 corresponds to tooth 33 of the flywheel, cylinder 6 FTDC corresponds to tooth 53, cylinder 3 FTDC corresponds to tooth 61, cylinder 5 FTDC corresponds to tooth 81, cylinder 4 FTDC corresponds to tooth 91, cylinder 7 FTDC corresponds to tooth 111, cylinder 2 FTDC corresponds to tooth 13, and cylinder 8 FTDC corresponds to tooth 23. This is illustrated in Figure 5.1.2.

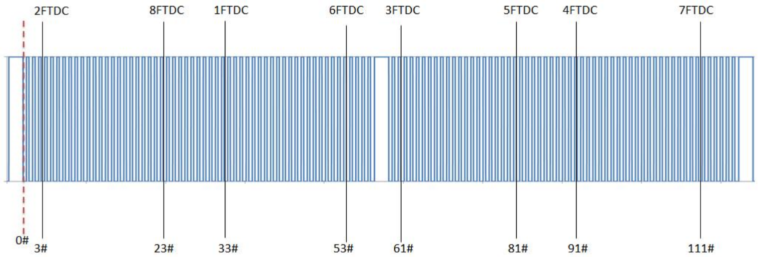

Figure 5.1.2 Relationship between Crankshaft Gear Signal Disc and FTDC Phase of Each Cylinder

Based on the original signal data of the crankshaft and camshaft speeds, along with the working phase relationship of each cylinder's compression top dead center corresponding to the teeth on the crankshaft gear signal plate, the instantaneous speed of each cylinder's power stroke can be calculated.

5.2 Speed Calculation

When the engine completes one cycle, the crankshaft rotates two full revolutions, passing through 116 teeth on the crankshaft position sensor, generating 116 pulse signals. On the other hand, the camshaft rotates one full revolution, and the camshaft speed sensor generates only one pulse signal.

calculate the time interval T_0 between the falling edges of two adjacent pulses, and based on the formula for speed calculation: $f=\frac{NZ}{60}$, where N represents speed and Z represents the number of teeth, the formula for calculating the speed of the crankshaft per pulse is as follows.

$$n_{crank} = \frac{1}{60 * T_0}$$

T_0: Pulse time, unit (s) ; n_{crank}L unit (rpm) .

The instantaneous crankshaft speed fluctuation curve for one operating cycle of the engine is shown in Figure 5.2.

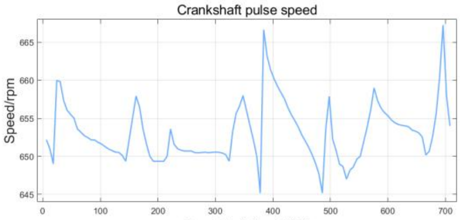

Figure 5.2 Crankshaft Instantaneous Speed Fluctuation Curve under Idle Conditions

In the above Figure 5.2, the first speed fluctuation curve represents the power stroke speed of cylinder 2, following the engine firing sequence, subsequent speed fluctuation curves correspond to cylinders 8, 1, 6, 3, 5, 4, and 7. From the figure 5.2, it can be observed that under idle conditions, the engine operation exhibits a certain level of unevenness, with peak values fluctuating between 653.6 rpm and 667.3 rpm and valley values fluctuating between 645 rpm and 650.2 rpm. However, overall, there is a trend of initially increasing and then decreasing.

5.3 Study on Cylinder-to-Cylinder Nonuniformity

The capability of each cylinder during the power stroke can be represented by the maximum speed reached during the power stroke minus the speed at the compression top dead center[5]. This value indicates the work capacity of each cylinder and is referred to as the speed fluctuation amplitude n.

$$\mathrm{n} = \mathrm{n}_{\mathrm{peak}} - \mathrm{n}_{\mathrm{FTDC}}$$

Therefore, the mean value of the fluctuation amplitudes for all cylinders is denoted as $\bar{\mathrm{n}}$.\

$$\bar{\mathrm{n}} = \frac{\sum_{\mathrm{i}=1}^{8} \mathrm{n}_{\mathrm{i}}}{8}$$

i represents the number of cylinders.

Comparing the fluctuation amplitudes of each cylinder with the mean fluctuation amplitude allows us to determine the nonuniformity degree of each cylinder, denoted as e.

$$\mathrm{e} = \mathrm{n} - \bar{\mathrm{n}}$$

The fluctuation in rotational speed and the nonuniformity degree of each cylinder are calculated as shown in Figure 5.3.1.

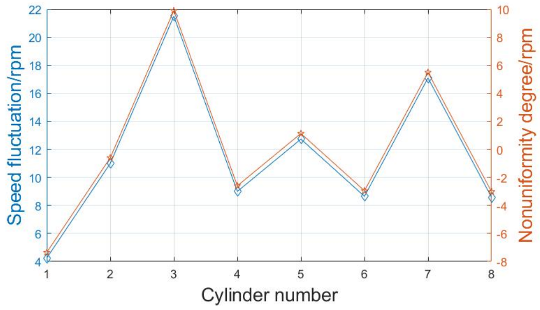

Figure 5.3.1 Calculated Results of Fluctuation Amplitudes and Nonuniformity Degree

The calculation results of the cylinder speed fluctuations and non-uniformity from Figure 5.3.1 indicate the presence of certain differences in the output power of each cylinder. The speed fluctuations range from 4.2 to 21.5 rpm. The third cylinder exhibits the highest speed fluctuation at 21.5 rpm, indicating the strongest output power. In contrast, the first cylinder has a speed fluctuation of only 4.2 rpm, suggesting the lowest output power.

From the calculation results of cylinder speed non-uniformity, it is evident that the third cylinder deviates the most from the mean speed fluctuation value, reaching 9.9 rpm, indicating the highest non-uniformity. The first cylinder also exhibits significant non-uniformity, with a value of -7.5 rpm, second only to the third cylinder, suggesting that the first cylinder's output power is below the average. Subsequent design control strategies will be needed to increase its fuel injection quantity to improve the non-uniformity of each cylinder. The cylinder with the lowest non-uniformity is the fifth cylinder, with a non-uniformity of 1.1 rpm.

As the 234V8 methanol engine employs multi-point injection technology, resulting in good fuel injection consistency among cylinders, the non-uniformity across cylinders is primarily caused by inconsistent air intake volumes. Therefore, the utilization of the GT-Power one-dimensional engine simulation software was employed to calculate the air intake volume for each cylinder, as depicted in Figure5.3.2.

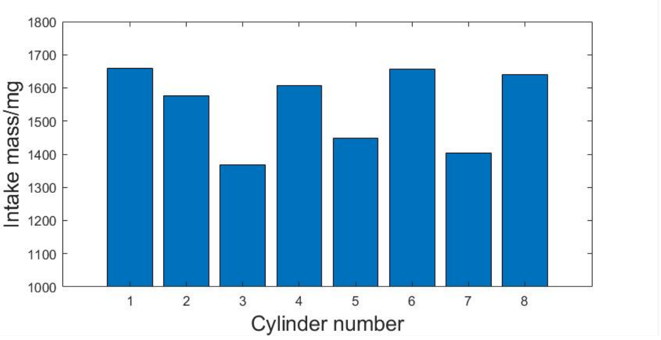

Figure 5.3.2 Air Intake Volume for Each Cylinder

From the above figure5.3.2, it can be observed that there is a certain level of non-uniformity in the intake volume across cylinders, ranging from 1367mg to 1660mg. Among them, the intake volume of the third cylinder is the lowest at 1367mg. Consequently, the air-fuel mixture is richer in the third cylinder, resulting in better combustion efficiency, thereby indicating that the third cylinder has the strongest output power, confirming its highest speed fluctuation. The intake volume of the seventh cylinder is also relatively low at 1403mg, following closely behind the third cylinder. The cylinder with the highest intake volume is the first cylinder at 1660mg. Analyzing this in conjunction with the results of the speed fluctuation calculations for each cylinder reveals that the air-fuel mixture in the first cylinder is leanest, leading to the poorest combustion efficiency and weakest output power, hence exhibiting the smallest speed fluctuation.

6. Conclusion

This study utilized Labview graphical programming software to perform the raw data acquisition of the crankshaft and camshaft speed signals of the 234V8 methanol engine. By processing the speed signals, the instantaneous crankshaft speed was calculated. Furthermore, in combination with the data on the air intake volume for each cylinder, an analysis of the non-uniformity across cylinders was conducted. The following conclusions were drawn from the analysis.

(1) The NI data acquisition device communicates with the host computer through Ethernet, and the Labview graphical programming software is utilized for the acquisition of the raw speed signals. This process ultimately yields accurate crankshaft and camshaft speed signals.

(2) Based on the speed calculation results, it was observed that under idle conditions, the engine operation exhibited a certain level of non-uniformity. The peak values fluctuated within the range of 653rpm to 666.7rpm, while the valley values fluctuated within the range of 645rpm to 649rpm. However, overall, there was a trend of initially increasing and then decreasing. According to the speed fluctuation analysis, the third cylinder had the strongest output power, while the first cylinder had the lowest output power. Furthermore, based on the calculation of non-uniformity across cylinders, it was found that the third cylinder had the highest level of non-uniformity, followed by the seventh cylinder, while the fifth cylinder had the lowest non-uniformity with a value of 1.1rpm.

(3) Using the engine one-dimensional simulation software GT-Power to calculate the intake volume of each cylinder, it is observed that the variation in the power output of each cylinder is due to differences in the intake volume. A lower intake volume results in a richer air-fuel mixture and stronger power output, leading to larger fluctuations in cylinder speed. Conversely, a higher intake volume creates a leaner mixture and weaker power output, resulting in smaller fluctuations in cylinder speed.

7. Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

8. Acknowledgements

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