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Benefits of the Electromagnetic Actuated Valve Train in Gasoline Engine Application

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ABSTRACT

Engines equipped with camless valve trains will have greater space for performance optimization. In this paper, based on the electromagnetic actuated valve train system, one-dimensional and three-dimensional simulation models on engine thermodynamic cycle and in-cylinder charge motion are established, respectively. With the application of early-intake-valve closing (EIVC) strategy, unthrottled load control and Miller cycle are obtained and their effects on engine pumping losses and NO_x emission are researched. The variation of engine in-cylinder charge movement intensity, pumping losses and volumetric efficiency are also revealed at variable intake valve actuation (VIVA). In addition, a particular variation trend of engine pumping losses, increasing in proportion to the engine load, is detected with the application of unthrottled load control. Finally, Genetic Algorithm (GA) is adopted to optimize engine performance with the EAVT system. Compared to engine with a camshaft valve train, the electromagnetic actuated valve train (EAVT)-driven engine shows a significant improvement on fuel consumption, power performance and NO_x emission.

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1. INTRODUCTION

In engines equipped with camless valve trains, the motion of the valves can be flexibly controlled as the engine working condition varies [1-4]. Thus, high-efficiency thermodynamic technology such as EIVC, Miller cycle and VIVA can be achieved, and the performance of engine economy, power and NOx emission will be significantly improved [5-9].

Ali Mohammad Pourkhesalian et al. investigated the effect of variable exhaust valve timing on engine internal exhaust gas recirculation (IGR), NOx formation and brake specific fuel consumption (BSFC), then a multi-objective optimization algorithm was applied to find the optimum timing and lift duration of the exhaust valve [10]. Wayne Moore et al. verified that the implementation of intake valve deactivation and EIVC strategies could improve the in-cylinder charge motion and combustion stability while had little impact on engine volumetric efficiency under low load and speed conditions [11]. Based on a 2L four-cylinder engine equipped with an electromagnetic valve actuation, V.Picron et al. confirmed that the adoption of intake valve deactivation and cylinder deactivation could reduce engine fuel consumption substantially when compared with the traditional engine with fixed valve timings [12]. Ruilin Liu et al. researched the in-cylinder tumble and inclined swirl and confirmed the benefits of SIV strategy on the In-cylinder charge movement [13]. Alkidas et al. reviewed recent advancements made in gasoline engine and remarked that flexible valve actuation was a key technology for decreasing fuel consumption [14, 15].

This paper proposes a new type of camless valve train using moving-coil electromagnetic linear actuator, and describes results of investigations conducted with a 1.6L four-cylinder gasoline engine equipped with the EAVT system, then documents the potential of NOx reduction, fuel consumption improvement and torque output optimization when using EIVC, Miller cycle, and VIVA strategies. The present paper is divided into four

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parts. First, the working principle of the EAVT is introduced, and simulation models are established. Then, details on the effects of Miller cycle on NOx emission are given. Moreover, the comparisons between single intake valve (SIV) and dual intake valve (DIV) mode are discussed. Finally, fuel economy and power performance are optimized by using Genetic Algorithm (GA).

2. OVERVIEW OF THE EAVT

2. 1. Test of the EAVT The EAVT system shown in Figure 1 mainly consists of a DC power supply, a controller and the EAVT prototype. The EAVT composes with an electromagnetic moving-coil linear actuator and permanent magnets with Halbach-array layout. A position sensor is used to provide the displacement feedback signal. By controlling the direct current in the moving coil, lorentz force is generated and actuates the valve to open and close.

As shown in Figure 2, a step current is adopted to accelerate valve opening or closing to achieve a short transition time (5ms).

Then, an adverse step current is used to decelerate the valve motion to obtain a promising valve seating velocity immediately, and an outstanding valve seating performance (0.1m/s) is obtained. Low positive and negative currents are used to keep the valve widely open (8mm) and closed respectively to minimize the power consumption of the EAVT.

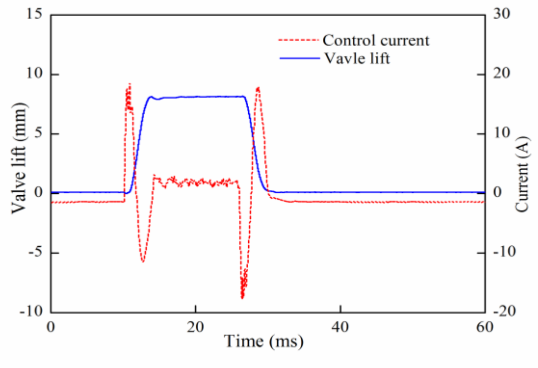


Figure 2. Performance test

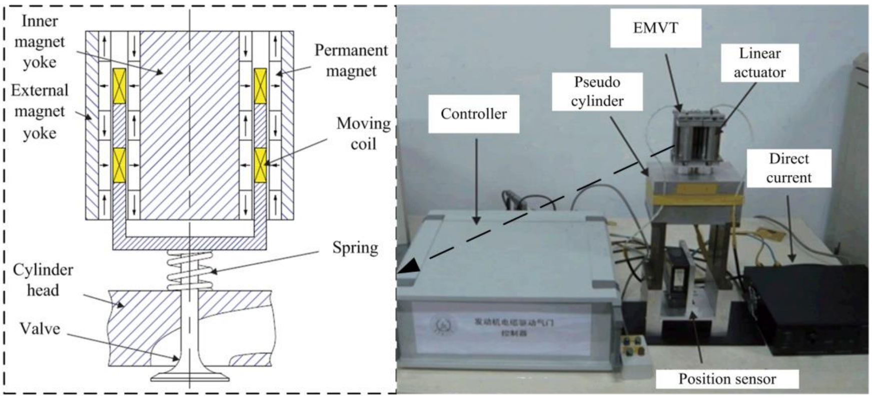


Figure 1. EAVT system

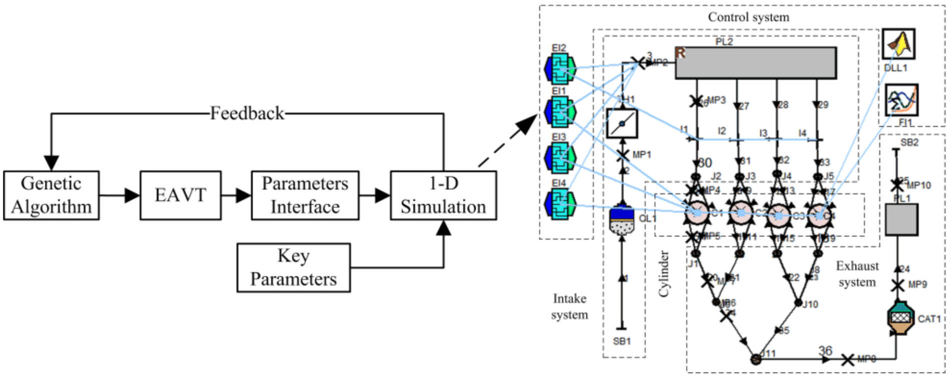


Figure 3. Co-simulation platform

2. 2. Simulation Models An optimization platform based on GA and one-dimensional simulation model is established as shown in Figure 3. According to the feedbacks of the one-dimensional simulation model, the GA module optimizes valve events, including valve timing, lift and duration, to achieve the most promising volumetric efficiency at full loads and the best fuel economy at part loads.

The one-dimensional simulation model of a 1.6L four-cylinder gasoline engine is established to calculate engine thermodynamic cycle and its accuracy has been verified [16]. The key parameters module is adopted to input key parameters for the simulation model, including thermodynamic parameters, friction factors and air-fuel ratio. The EAVT and parameters interface modules are applied to generate and transfer the valve motion curves. A three-dimensional simulation model using computational fluid dynamics (CFD) method is created to research the in-cylinder charge motion under variable valve actuation strategy. Figure 4 shows the dynamic grid for the CFD model.

3. BENEFITS OF EIVC STRATEGY

With the application of EIVC strategy based on the EAVT system, unthrottled engine load control is achieved by regulating the intake valve closing timing. Thus, the engine pumping loss decreases significantly as shown in Figure 5. Compared to the original engine with a camshaft valve train, the pumping loss of the EAVT-driven engine plummets by 81.3% at 1600 r/min and 0.29 MPa BMEP engine working condition.

On the other hand, as the intake valves are closed before the intake bottom dead centre, the in-cylinder mixture experiences an expansion process during the later period of the induction stroke, and Miller cycle is obtained due to the enlargement of the engine effective expansion ratio.

Figure 6 shows the in-cylinder mixture temperature at 1600 r/min and 0.29 MPa BMEP engine working condition. Because of Miller cycle, low-temperature induction, compression and power strokes are obtained.

As shown in Figure 7, at 1600 r/min engine working conditions, compared to the camshaft-driven engine, an obvious reduction of engine NO_x emission is obtained in the engine using the EVAT system because of the low-temperature combustion caused by Miller cycle.

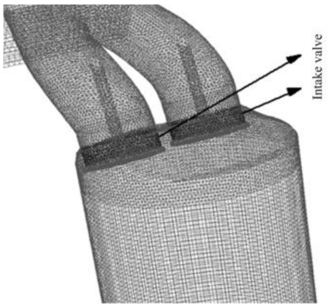


Figure 4. Numerical grid for CFD model

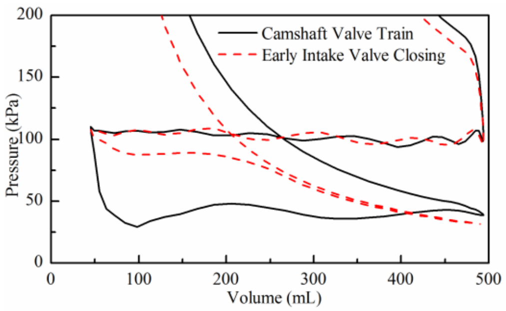


Figure 5. P-V diagram at 1600 r/min and 0.29 MPa BMEP engine working condition

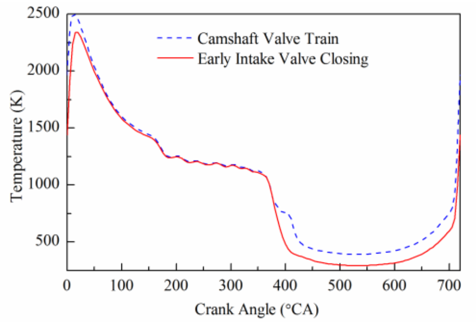


Figure 6. In-cylinder mixture temperature

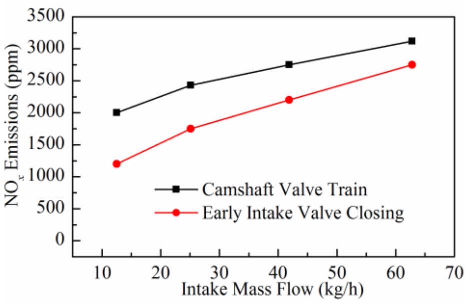
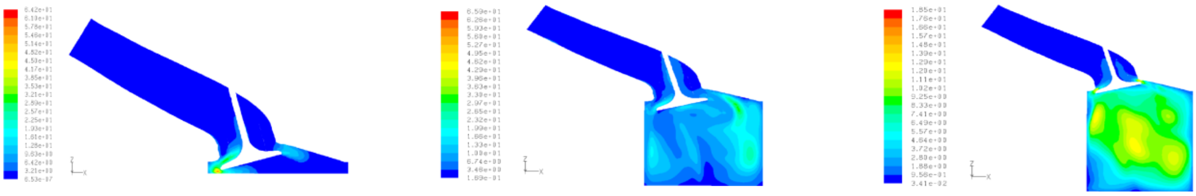


Figure 7. NO_x emission at 1600 r/min

4. BENEFITS OF VIVA

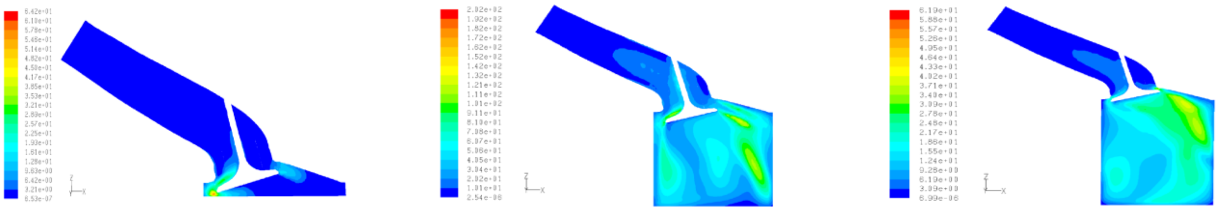
4. 1. Improvement of In-cylinder Charge Movement using SIV Mode

The most promising valve trains should be able to alter valve operation mode as the engine working condition varies. The engines equipped with the EAVT system can operate in the single intake valve (SIV) or dual intake valve (DIV) mode. Compared with the DIV mode, the SIV strategy improves the in-cylinder charge movement intensity dramatically during the medium term of the induction stroke as shown Figures 8 and 9.



(a) 20 ºCA (b) 110 ºCA (c) 170 ºCA

Figure 8. Turbulent Kinetic Energy of the DIV Mode at 1200 r/min



(a) 20 ºCA (b) 110 ºCA (c) 170 ºCA

Figure 9. Turbulent kinetic energy of the SIV Mode at 1200 r/min

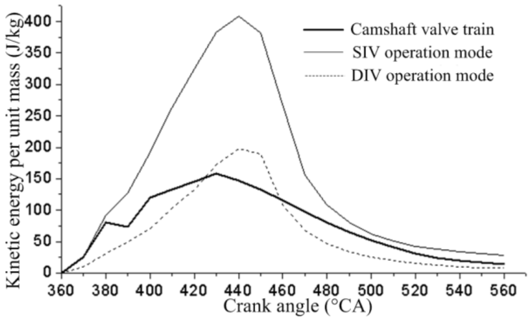


Figure 10. Kinetic energy per unit mass

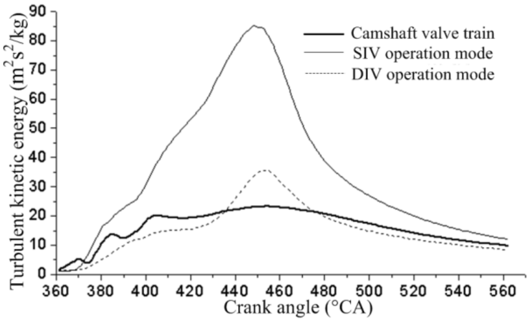


Figure 11. Turbulent kinetic Energy per unit mass

Moreover, the difference of the in-cylinder charge kinetic energy and turbulent kinetic energy per unit mass between the SIV and DIV mode is inconspicuous during the initial stage of the induction stroke, and mixture with higher movement intensity mainly concentrates around the intake valve seats. However, with the advance of the intake process, the SIV mode demonstrates its overwhelming superiority on the promotion of in-cylinder charge movement intensity. Figures 10 and 11 show the kinetic energy per unit mass and the turbulent kinetic energy per unit mass at 1600r/min 0.48MPa BMEP engine working condition.

4. 2. Inconspicuous Pumping Losses between SIV and DIV Mode

Compared with the traditional gasoline engine using throttle to regulate engine load, the pumping losses of the engine using unthrottled load control presents a diametrically opposed change trend as shown in Figure 12.

The pumping mean effective pressure (PMEP) of the EAVT-driven engine increases in proportion to the engine load, while the pumping losses of the camshaft-driven engine decrease as the throttle opening enlarges.

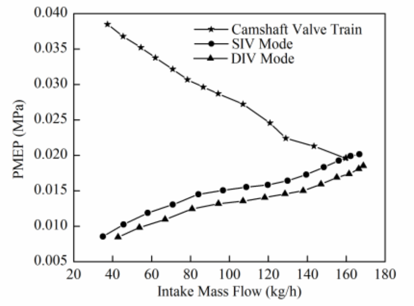


Figure 12. PMEP under variable valve actuation

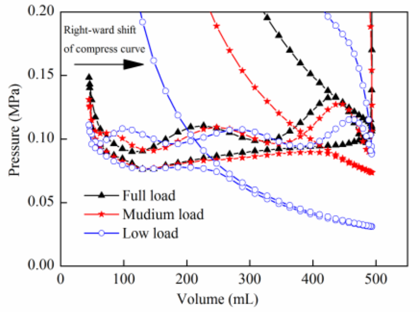


Figure 13. P-V diagram with SIV mode

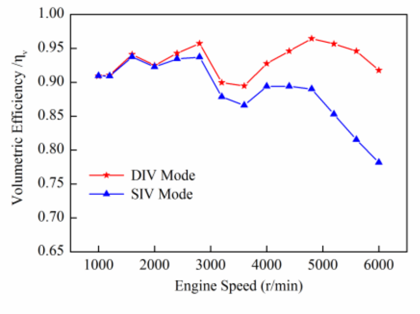


Figure 14. Volumetric efficiency under full loads

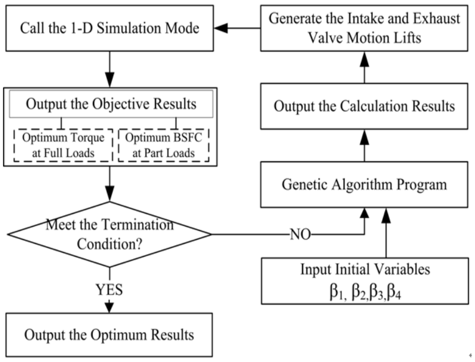


Figure 15. Optimization procedure

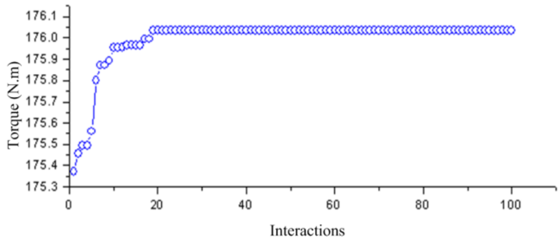


Figure 16. Interaction procedure

The P-V diagram at the speed of 2800 r/min presented in Figure 13 reveals the reasons. As EIVC strategy is implemented to regulate the engine load, so with the enlargement of the engine load, the intake valve closing angle is delayed to inhale more fresh air. As a result, the pumping losses increase with the right-ward shift of the compression curve. Furthermore, due to the reduction of the effective flow cross-sectional area, the pumping losses of the SIV mode raise slightly as compared with the DIV mode.

At low engine speeds, the difference of volumetric efficiency between the SID and DIV mode is negligible, as shown in Figure 14. With the increase of engine speed, the disadvantage of the SIV mode on engine volumetric efficiency becomes increasingly evident. Especially at high speeds, the IVDA strategy reduces volumetric efficiency by an average of 10%.

In general, for the 1.6L gasoline engine with the EAVT system, the SIV mode takes priority over the DIV mode under engine low speeds (≤2800 r/min), where volumetric efficiency can be guaranteed and charge motion can be improved significantly. However, at high speed conditions, the DIV operation is preferably adopted to ensure engine power performance.

5. ECONOMY AND POWER PERFORMANCE OPTIMIZATION

To explore the EAVT-driven engine part-load fuel consumption and full-load torque output potential, a multi-objective optimization based on GA is created as shown in Figure 15.

The initial variables β_1, β_2, β_3, β_4 are the intake valve opening timing (IVO), intake valve closing timing (IVC), exhaust valve opening timing (EVO), exhaust valve closing timing (EVC). By the interactive calculation of the GA program, the preliminary results of β_1, β_2, β_3, β_4 are obtained, and then converted to valve motion lifts in the subroutine used for generating valve motion lifts. The volatility of the objective results is set up as the termination condition, if the fluctuation range is lower than the point value, the optimization program stops and optimum results are obtained.

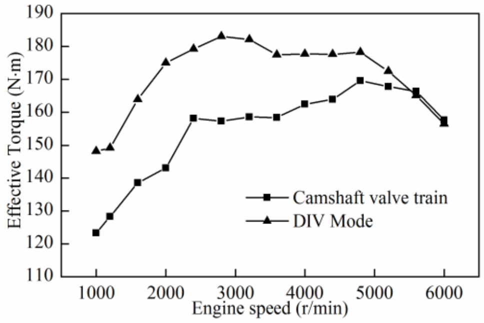
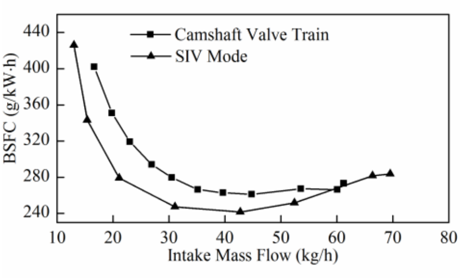
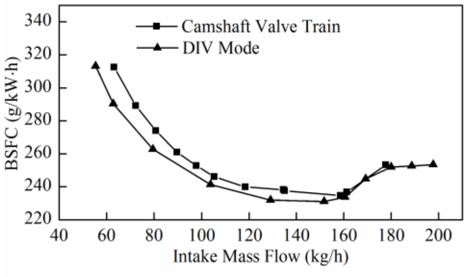


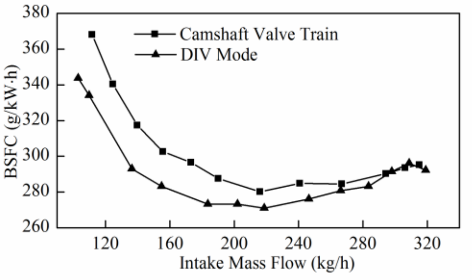
Figure 17. Optimization of engine effective torque



(a) 1200r/min



(b) 3200r/min



(c) 5200r/min

Figure 18. Optimization of fuel consumption

Figure 16 shows the iteration convergence rules of the objective torque. The effective torque converges to 176.03N.m after twenty interactions.

Figure 17 illustrates the promotion of engine effective torque output at full load conditions. Compared with the camshaft-driven engine, the EAVT-driven engine, with an average increase of 12.84% on engine effective torque under low and medium speeds, shows an outstanding power performance. However, at high speed conditions, the relatively long transition time (4ms equals to 134.4°CA at the speed of 5600 r/min) weakens the advantage of the EAVT system on engine power performance.

The part-load fuel consumption potential of the unthrottled engine using EAVT is evaluated as shown in Figure 18. Due to the obvious reduction of pumping losses under low and medium load conditions, an average 9.5% BSFC improvement is achieved. With the enlargement of engine load, throttle opening increases and the advantage of unthrottled load control on fuel economy decreases gradually. At high load conditions, as the widely open throttle minimizes pumping losses, the economic difference between throttled and unthrolled load control becomes inconspicuous.

6. CONCLUSIONS

A new type of camless valve train, using moving-coil as electromagnetic linear actuator is proposed in this paper, and outstanding performance of the EAVT system is obtained.

With the implementation of the EAVT system, on one hand, unthrottled load control is obtained and a significant reduction of pumping losses is achieved. On the other hand, due to the enlargement of the engine effective expansion ratio, Miller cycle and low-temperature are achieved and NO_x emission is improved.

By using unthrottled load control strategy, a particular variation trend of engine pumping losses, increasing in proportion to the engine load, is detected.

As the difference of pumping losses between the SIV and DIV mode is inconspicuous under all engine working conditions, so the SIV mode takes priority over the DIV mode at engine low speeds to improve the in-cylinder charge motion, and the DIV operation is preferably adopted to ensure engine power performance at high speed conditions.

An average 12.84% effective torque increase at full load conditions and 9.5% fuel consumption improvement at part load conditions are obtained for the engine using the EAVT system. However, deeper research is required to lessen the relatively long transition time at high speed conditions.

7. ACKNOWLEDGMENT

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چکیده

موتورهای مجهز به قطار سوپاپ camless فضای بیشتری برای بهینه سازی عملکرد خواهند داشت. در این مقاله، بر اساس سیستم قطار دریچه فعال الکترومغناطیسی، مدل های شبیه سازی یک بعدی و سه بعدی به ترتیب بر روی چرخه ترمودینامیکی موتور و حرکت بار درون سیلندری تاسیس شده است. با استفاده از استراتژی بسته شدن زود هنگام شیر (EIVC)، کنترل بار unthrottled و چرخه میلر به دست آمد و اثرات آنها بر فقدان پمپاژ موتور و نشر NOx مورد تحقیق قرار گرفته است. تغییر شدت حرکت باری درون سیلندری موتور، تلفات پمپاژ و راندمان حجمی نیز در تحریک سوپاپ مصرفی متغیر (VIVA) آشکار شده است. علاوه بر این، یک روند انحرافی از فقدان پمپاژ موتور، افزایش نسبت به بار موتور، با استفاده از کنترل بار unthrottledشناسایی شده است .در نهایت، الگوریتم ژنتیک (GA) با عملکرد موتور بهینه سازی شده با سیستم EAVT منطبق شده است .در مقایسه با موتور با قطار شیر میل بادامک، هر موتور رانده شده با قطار دریچه فعال (EAVT) الکترومغناطیسی بهبود قابل توجهی در مصرف سوخت، عملکرد قدرت و نشر NOxنشان می دهد.

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