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Research on Working Characteristics of Coupled Dynamics Linear Hydrogen Internal Combustion Engine Based on Electromechanical Integration

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ABSTRACT. *The special free piston movement of the linear hydrogen internal combustion engine results in a lower combustion reaction rate and an equal volume degree of heat release. In order to reduce the loss of combustion time and improve the efficiency of energy utilization, pilot lean combustion technology was tried in a linear hydrogen internal combustion engine. Based on mechatronics, the dynamics and kinematics simulation analysis and experimental study of valve train of linear hydrogen internal combustion engine are carried out in this paper. The feasibility of lean burn technology is verified by principle test, and then the combustion performance and operation characteristics of linear hydrogen fuel internal combustion engine are simulated by an iterative calculation method coupled with piston motion. Compared with the traditional hydrogen internal combustion engine, the combustion duration of linear hydrogen internal combustion engine is longer, the maximum combustion pressure and average temperature are smaller, which is conducive to nox emission control, but the combustion isovolumetric heat release is less, the afterburning is more serious, and the indicating efficiency is lower. This provides valuable reference for the performance evaluation and optimal design of valve train.*

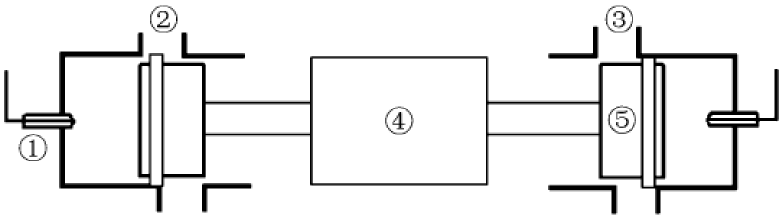
KEYWORDS: *Electromechanical integration, Coupling, Linear hydrogen internal combustion engine, Operating characteristic*

1. Introduction

Electromechanical integration products are equipment and devices including mechanical subsystems, servo drive subsystems with controllers, and information exchange subsystems of the two, such as space shuttles, robots and machine tools [1]. With the development of modern science and technology, as well as the objective environment of shortage of petroleum resources and increasingly strict environmental laws and regulations, internal combustion engine technology is developing in the direction of high power density, low fuel consumption, low pollution, low noise and high reliability [2]. Linear hydrogen internal combustion engine is a new type of engine without crank-connecting rod mechanism. Its piston motion is not limited by mechanical mechanism, and can realize variable compression ratio operation. It has the advantages of strong fuel adaptability, small mechanical loss, flexible output power, etc. Improve the power and economy; on the other hand, it is hoped that the valve mechanism will bear relatively small heat and force load in the process of motion, with small acceleration, so that the vibration and noise will be reduced in the middle and high-speed operation of the internal combustion engine, and the engine life and running stability will be improved [3]. Based on the mechatronics, the coupling model of the working process of the linear hydrogen internal combustion engine is further established in this study. The simulation analysis of its working performance is carried out to explore the possible performance characteristics of the piston motion, combustion heat release and emission of the linear hydrogen internal combustion engine, so as to provide guidance for further prototype test research

2. Principle of Linear Hydrogen Internal Combustion Engine

The generally researched linear hydrogen internal combustion engine generally works in a two-stroke mode, adopts a double-engine opposite arrangement and a flexible load device is arranged in the middle. In this paper, a linear motor is used as the load, and the structure of the whole linear hydrogen internal combustion engine is shown in Fig. 1. The valve mechanism of the whole internal combustion engine is driven by a valve cam, and the design of the cam plays a decisive role in the motion performance of the valve mechanism [4]. The profile of the valve cam determines the lift, opening and closing time, opening and closing range of the intake and exhaust valves, the acceleration type of the intake and exhaust valves, the smoothness of the buffer transition and other characteristics. Different from traditional internal combustion engines, the motion of linear hydrogen internal combustion engines is affected by multiple forces, of which the in-cylinder gas force is a key influencing parameter, and the piston motion and combustion are coupled with each other [5]. The servo system not only provides power for the mechanical system, but also has a very important impact on the control accuracy of the system. Therefore, it is necessary to build a simulation platform of servo system, and take the influence of servo system into account in the early stage of mechatronics system design. When the piston moves to the predetermined fuel injection position, the combustible hydrogen is injected directly into the combustion chamber by the injection system, at this time, the linear motor is converted from the power mode to the power generation load mode. These will be directly related to the inflation efficiency, fullness coefficient, time face value, running stability and contact stress between components of the internal combustion engine. So the design of cam is the core of valve train design.



①-Spark plug; ②-Exhaust port; ③-Intake port;

④-Load; ⑤-Piston.

Fig.1 Structure Diagram of Linear Hydrogen Internal Combustion Engine

3. Working Process Model

3.1 Coupling Modeling Method

For linear hydrogen internal combustion engines, the piston motion is not constrained by mechanical mechanisms, and has the characteristics of variable stroke and variable motion laws. Moreover, the motion laws of the piston have an important influence on the combustion process of the internal combustion engine, so the calculation and analysis of the combustion heat release of the linear hydrogen internal combustion engine are different from the combustion simulation of the traditional internal combustion engine [6]. If every object constituting the system is treated as a rigid body, the mechanical system is called a multi-rigid body system. If the elastic deformation of each object in the system is fully considered and each object is considered as a flexible body, then the mechanical system is a multi-flexible body system. The application of diesel ignition technology in linear hydrogen internal combustion engine can not only improve the combustion speed of linear hydrogen internal combustion engine, but also further realize lean combustion and reduce NOx emission [7]. It provides the best performance and the most reliable results for each conventional valve train. From the design of cam profile to the dynamic simulation of the whole valve system, it can effectively support the arrangement and design of the valve mechanism of single cylinder and the whole machine. Therefore, there is a coupling relationship between the dynamic model and the combustion CFD model In order to accurately simulate the performance characteristics of the linear hydrogen internal combustion engine, the coupling iteration method is used to calculate the dynamic model and CFD model. Therefore, it is necessary to develop a method to facilitate the computer to identify the connection status and constraint forms between rigid bodies, so as to achieve the purpose of automatically eliminating the relevant constraint counterforce [8]. Under high compression ratio, higher in-cylinder gas pressure and temperature will also increase the combustion activity of in-cylinder hydrogen fuel to a certain extent, thus advancing the maximum combustion pressure.

3.2 Dynamic Model

The multi-body system dynamics model is essentially a process of abstracting and digitizing the overall model of the mechanical system. When establishing the ventilation model, the piston movement results are taken as the basis for opening and closing the intake and exhaust valves, and the piston movement is followed to simulate each stage of the ventilation process respectively, and the calculation results are transferred to the combustion model.

According to the structure and working principle of linear hydrogen internal combustion engine, the dynamic equation of piston assembly is as follows:

$$md^2x / dt^2 = F_P - F_T - F_L$$

Where: m is the mass of piston assembly; X is the displacement; T is time; FP is the in-cylinder gas acting force of engines on both sides; Ff is the system friction force; FL is the load force. Where FF and FL can be described as:

$$F_T = C_f dx / dt;$$
$$F_L = C_L dx / dt,$$

Where: CF is viscous friction coefficient; CL is electromagnetic damping coefficient of load motor

For FP, it can be obtained by calculating the in-cylinder gas pressure on both sides. At present, the thermodynamic equation of in-cylinder gas pressure change of linear internal combustion engine derived by existing research is as follows:

$$\frac{dp}{dt} = \frac{\gamma - 1}{V}\left(\frac{dQ_c}{dt} - \frac{dQ_h}{dt}\right) - \lambda \frac{p}{V},$$

Where: γ is the specific heat capacity ratio; V is the cylinder volume; Qc is the energy released by combustion; Qh is the loss of energy through heat transfer.

During the operation of the valve train, the valve repeatedly impacts the valve seat ring, and there is generally no lubrication condition during the operation. Therefore, the friction and wear between the valve and the valve seat ring is one of the main failure modes [9]. The principle is to analyze the mathematical model of asynchronous motor directly in the stator coordinate system by using the analysis methods of space vector and stator magnetic field orientation, and calculate the flux linkage and torque of the motor by simply detecting the stator voltage and current of the motor and using the instantaneous space vector theory. According to the geometric structure of the prototype and the position of the piston at the end of the air exchange, the enclosed gas space in the cylinder is meshed. The rigid body model is convenient for modeling and calculation, but its calculation result is not as accurate as the flexible body model. In the actual engineering research, the resonant frequency of the structural system should be selected according to the actual research situation [10]. Therefore, in the actual design, the resonant frequency of the structural system should be as high as possible It is much higher than the resonance frequency of the electromechanical system, so as to keep the enough bandwidth of the electromechanical system and avoid the electromechanical coupling resonance

3.3 Verification of Model Validity

In order to verify the correctness of the coupling model, the calculation model is verified by using the test data of linear hydrogen internal combustion engine with the same structural parameters in reference [7]. the relationship between the calculated in-cylinder pressure p of linear hydrogen internal combustion engine and the equivalent rotation angle φ and the test results are shown in Fig. 2. under the action of external force, the dynamic response of the mechanism is studied, including the system's position, speed, acceleration, constraint reaction force generated in the movement process and other parameters. In the design of cam profile, the peak of positive acceleration and the peak of negative acceleration are often used as constraints to control the contact stress of cam and prevent the valve from flying off in the mechanism. The enlarged Fig. shows that the actual angular speed fluctuates up and down around the ideal angular speed, and the frequency is very large, because the direct torque technology takes the electromagnetic torque as the final control target

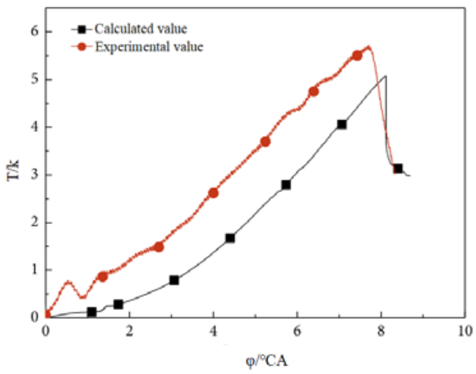


Fig.2 Verification of Calculation Results

From the comparison of the cylinder gas pressure curve in Fig. 2, the change trend of the calculation results and the test data is basically the same, the overall data comparison deviation is small, the maximum error of the calculation and test data is within 6%. The relative position of the rigid body remains unchanged, and the coordinate system moves with the motion of the rigid body. The position of each particle on the rigid body can be determined by the invariant vector of the conjoined coordinate system. The in-cylinder pressure difference between the two modes is small before the fuel starts to burn, and the peak value of pressure rise rate caused by ignition increases after the combustion starts. At the same time, it can be seen that the valve movement is smooth, too smooth, and there is no big mutation. The negative acceleration interval is large and the dynamic performance is good at this characteristic velocity.

4. Performance Characteristics

4.1 Kinetic Analysis.

After several coupling and iterative calculations of the dynamic model and the combustion CFD model, the piston dynamic characteristics of the linear hydrogen internal combustion engine are obtained, and the piston dynamic curves of the traditional hydrogen internal combustion engine with the same piston stroke are compared as shown in Fig. 3. The piston motion of the two engines is totally different. The linear hydrogen internal combustion engine has a larger peak acceleration A, but the peak piston speed V is smaller than that of the conventional hydrogen internal combustion engine. A set of variables that uniquely determine the positions and orientations of all components in the mechanism. Generalized coordinates can be changed arbitrarily (i.e. independent) or meet certain constraints (i.e. not independent). In the motion system, the generalized coordinate system changes with time.

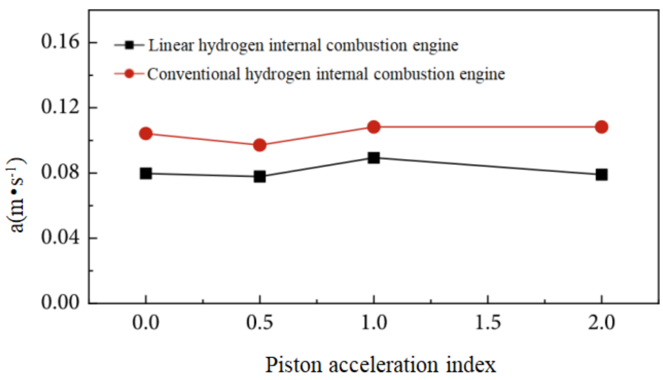


Fig.3 Dynamic Characteristics of Piston in Linear Hydrogen Internal Combustion Engine

The average temperature of in-cylinder gas caused by ignition combustion near top dead center is significantly higher than that caused by spark ignition, but ignition produces higher in-cylinder gas temperature in the middle and later stages of expansion stroke. The contact force and contact stress between the cam and the rocker arm are continuous, which indicates that there is no separation phenomenon during the working contact between the cam and the rocker arm. This is because the piston motion of the linear hydrogen internal combustion engine is not constrained by the mechanical mechanism, and the peak gas explosion pressure caused by the heat release of fuel combustion acts on the piston, and directly shows a large acceleration. In practical application, because the damping ratio of the structure is generally small, the influence of the peak value of the structure resonance on the system bandwidth cannot be solved by increasing the damping ratio of the structure alone, so the damping characteristics of the system should be increased as much as possible, and the resonance frequency of the structure should be increased.

4.2 Combustion Heat Release Characteristics

The cylinder pressure curves of linear hydrogen internal combustion engine, linear gasoline engine and traditional hydrogen internal combustion engine obtained by multiple iterative calculation of combustion process are shown in Fig. 4. It describes the basic idea and method of modeling and calculation in a general way, in which the solver is the core part, and different solvers set different algorithms, and iterative solution can be carried out only by setting iterative step length. The duration of pilot combustion is obviously shorter than the duration of ignition. About 80% of the fuel completes combustion near top dead center, and the combustion heat release equivalence degree is improved compared with the ignition mode, thus verifying the conclusion that pilot combustion improves the combustion equivalence degree of linear hydrogen internal combustion engine.

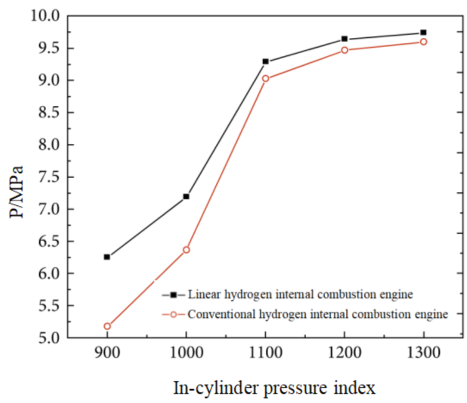


Fig.4 Comparison of in-Cylinder Pressure Changes

When the two engines take the same ignition advance angle, the traditional hydrogen internal combustion engine has the highest combustion pressure, followed by the linear hydrogen internal combustion engine, while the linear gasoline engine has the smallest, and the occurrence time of the highest combustion pressure is also different. It can be seen that under the condition of the same input fuel energy, the operation frequency of the internal combustion engine is increased due to the improvement of the combustion heat release efficiency, and the piston movement stroke is slightly larger than the ignition combustion result. The peak value of the pressure rise rate of the traditional hydrogen internal combustion engine is the largest, while that of the linear gasoline engine is the smallest. The calculation accuracy is different under different external loads. In the mechanism dynamics, the general component is to transfer the motion and force at the kinematic joint, so it is very important to reflect the boundary effect of the kinematic joint, especially when the force is large.

Compared with linear gasoline engine, the density of hydrogen fuel is smaller than that of gasoline, and the calorific value of the mixture formed by air is lower, which results in the same heat release. When the resonance frequency of the structure is far away from the resonance frequency of the system, there is only high-order resonance effect in the high-frequency segment. For the photoelectric theodolite, the effective bandwidth internal frequency characteristic of the servo system is normal, and the system has good dynamic performance. Because the number of moles of gas fuel can be compared with that of air, this mixing means that the pressure energy loss of gas fuel is larger, and H2 is greater than that of natural gas. And the peak value is higher than that of the linear gasoline engine, which makes the linear hydrogen internal combustion engine have higher indicating efficiency, but may also aggravate the possibility of deflagration. The valve lift of the flexible body is slightly smaller than that of the rigid body, but the difference between the two is very small in the calibrated rotational speed, and the valve lift and design index in both rigid and flexible modes are within 1%, indicating that valve deformation has little influence on valve lift. The calculation results have verified that ignition technology can accelerate the heat release process of linear hydrogen internal combustion engine and improve the combustion equivalence. This is mainly due to the ignition is similar to multi-point ignition, large area of high temperature diesel flame can fully ignite the surrounding lean mixture. Moreover, because the conventional hydrogen internal combustion engine is constrained by the crank connecting rod at this time, the piston acceleration is small, resulting in the maximum combustion pressure can be maintained for a longer time.

5. Conclusions

Based on mechatronics, the working process performance of linear hydrogen internal combustion engine is numerically simulated by coupling piston dynamics model and CFD combustion model, and the working process of traditional hydrogen internal combustion engine and linear gasoline engine is compared. Under the normal working state of the valve train, the valve clearance is actually a dynamic clearance. The higher the speed, the greater the movement inertia of the train, and the greater the maximum valve clearance. The adoption of pilot combustion technology is helpful to improve the combustion reaction speed of linear hydrogen internal combustion engine, the degree of heat release and the indication efficiency of linear hydrogen internal combustion engine; compared with linear gasoline engine, the combustion process of linear hydrogen internal combustion engine has fast flame propagation speed, short combustion duration, more heat release of equal capacity and rapid combustion period, and the post combustion phenomenon is not obvious. The reasonable combination of measures such as supercharging, intercooling, lean burn, high pressure injection and miller cycle can realize the clean and efficient use of H2 fuel in internal combustion engine. The peak strain of the push rod and rocker arm decreases with the increase of engine speed. Compared with ignition, the maximum in-cylinder combustion pressure and temperature caused by ignition are higher, but there are slight deficiencies in NOx emission.

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