Research on Working Process and Stability of Hydraulic Free Piston Engine

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Abstract—This paper studies the working principle of the hydraulic free piston engine, and details the related contents of the working process of the hydraulic free piston engine. The related contents include the analysis of working state, the analysis of fuel injection characteristics, the analysis of the air exchange system, the analysis of the operating parameters, the working process in the cylinder, etc. The stability of the hydraulic free piston engine is studied by establishing a nonlinear model. Based on this, the stability control strategy is developed, which aims to accumulate reliable experimental data and lay a good application foundation for developing the dynamic control of hydraulic free piston engine in working process.

1. Introduction
From the current market operation state, hydraulic free piston engine occupies a large share, it has the advantages of efficient operation, simple structure and so on, it has always been a research hotspot in the engine field. From the specific research situation, it is necessary to analyze the working process and working stability of the equipment, and on this basis to formulate the corresponding control strategy, so as to improve the operating stability of the engine and promote the healthy development of the engine industry.

2. Research on working principle of hydraulic free piston engine

Figure 1 Schematic diagram of working principle of hydraulic free piston engine
The working principle of the hydraulic free piston engine is shown in Figure 1. The main structure of the hydraulic free piston engine is to combine the compression chamber with the pump chamber. In specific application, the pressure of low-pressure oil will be raised to a certain pressure value, thus completing the automatic compression process of the engine. In the expansion stroke of the engine, the high pressure oil is output to the high pressure oil circuit through the check valve 4 and the damping hole 6. The accumulator 5 of the high pressure oil circuit is used to stabilize the pressure. The high pressure oil is transformed into the required oil pressure of the vehicle system by the hydraulic transformer 9, which drives the external output torque of the hydraulic motor. The back pressure of hydraulic motor is no longer atmospheric oil pressure, but secondary high pressure with a certain pressure. Accumulator 8 of secondary high pressure oil circuit is used for oil circuit pressure stabilization. The secondary high pressure oil line obtains the designed secondary high pressure through the pressure relief valve. When the pressure of the secondary high pressure oil line is insufficient, open the oil filling solenoid valve or start the hydraulic pump to obtain the oil pressure. It should be noted that when the engine is shut down for a long time, the secondary high pressure oil needs a special starting hydraulic pump to provide starting energy. After the engine high pressure oil system obtains enough hydraulic oil, the starting hydraulic pump is closed.

3. Research on the working process of hydraulic free piston engine

3.1. Work state analysis

3.1.1. Force of piston assembly

On the engine piston component stress analysis, need to clear the compression process, to control the pressure in the cavity as a dominant force, and the compression performance will be affected, and with the continuous increase of the pressure in the cylinder, piston components running situation, also under the comprehensive influence, interfere with the pressure point location changes. And the piston will also increase in volume under the action of combustion pressure in the cylinder. In the initial stage of volume expansion, the pressure in the hydraulic pump cavity has not been fully distributed, so the pressure generated at this time will also work directly on the piston, so that the piston assembly can obtain a large acceleration. With the advance of the expansion activity, the hydraulic oil in the pump chamber will also be transformed into high pressure oil. At this time, the piston assembly is subjected to the hydraulic resistance of the piston in the pump chamber, and the resultant force of the piston assembly in the direction of its central axis decreases. At this time, the acceleration of the piston assembly decreases, and the piston assembly moves to the bottom dead center under the action of inertial force.

3.1.2. Indicating work variation

In the application process of indicating power variation, the factors that need to be referred to include fuel injection lift, pre-injection fuel, exhaust valve opening time, etc. Taking the fuel injection lift as an example, its influence on indicating power variation is as follows: When the distance between the injection position and the zero point of displacement is too large, the fuel injection into the cylinder after a period of ignition retardation after ignition, and at this time because of the cylinder volume is large, the pressure rise rate is low, so the piston assembly continues to move up the dead center. At the same time, when the injection position is 19mm, the equivolumetric degree is low. On the contrary, when the injection position is reduced to 10mm, the combustion equivolumetric degree inside the engine will increase significantly. If the engine fires early, the piston assembly will slow down early, and the spacing between TDC and the cylinder head will increase, which will affect the steady increase of pressure in the cylinder. When the ignition position is close to the top surface of the cylinder head, the piston assembly in this state will still maintain a certain speed to work, to meet the requirements of constant volume combustion in the cylinder.
3.2. Injection characteristic analysis
According to the relevant content in the first chapter, it can be understood that the main working system involved in the operation of the hydraulic free piston engine includes the hydraulic piston pump system, cam-free intake and exhaust system, etc. Compared with other applications, the hydraulic free piston engine has no crank-connecting rod mechanism in its composition, which also requires the addition of a drive injection system to maintain the stability of the injection process. Currently use more fuel injection system with the pressurization injection system, regulated fuel injection system, etc., since the pressurized fuel injection system, for example, because the system will be combined with a steady improvement in the application situation in cylinder pressure, therefore in the fuel pump when the choice, should choose low pressure fuel pump to assist the system, so as to improve the flexibility of the system operation process. It is important to note that in the process of system analysis of spray characteristics, also need to do a good job of controlling the corresponding variables, but also of variables influence law on comb, and on the basic situation, from the perspective of the overall operation to complete the comprehensive analysis of the feasibility of fuel injection system running state, it also provides effective work for stability analysis of reference.

3.3. Analysis of ventilation system
During the working period of the hydraulic free piston engine, its main working principle is to use the electrohydraulic drive valve system to set up the ventilation channel, and use Roots pump to pressurize the air, and then pass into the ventilation system for work. At the same time, the exhaust system will exhaust exhaust gas directly out of the engine with the assistance of the driving hydraulic oil circuit to complete a process of air exchange. The specific schematic diagram of the system is shown in Figure 2.
At the same time, during the operation of the engine ventilation system, the valve opening state will be adjusted by means of the fuel intake battery valve. The higher the oil filling time, the slower the opening speed of the valve will be. At the same time, during the operation of the solenoid valve, the signal transmission speed generated by it will also be related to the signal transmission interval and the valve opening time, which is also the relevant content that should be paid attention to in the application adjustment process of the ventilation system. In addition, the engine hydraulic pressure drops faster, which will also bring greater impact on the valve, affecting the service life of the valve. Based on this, it is necessary to integrate the secondary pressure relief working mode into the system, which can quickly unload the pressure of the hydraulic chamber by 30%-50% in advance, and then open the hydraulic pressure relief valve to complete the unloading of the remaining pressure, thus improving the order of the working state of the system and prolonging the service life of the ventilation system [1].
3.4. Operating parameter analysis

3.4.1. Cold start process

In the cold start stage of engine, it is easy to be affected by the external environment, which makes the engine combustion process in a cyclic state, which will also have a great impact on the engine piston dynamics characterization. Combined with the existing data, the relevant data of the change process of TDC and BDC are sorted out, and the schematic diagram as shown in Figure 3 is obtained. According to the status shown in the figure can be learned, in the process of engine starting, the position of business data catalog will be larger fluctuations, from the developing trend of the whole, the main present a state of decline, the dead point position in the engine will to move in the direction of the top.
dead center, causing internal compression engine hydraulic shrinking, thus reduced the compression ratio. At the same time, the cylinder combustion pressure and pressure rise rate fluctuations were analyzed, from which it can be seen that when the engine starts, the maximum combustion pressure and pressure rise rate generated are relatively large, but with the engine running state gradually stable, the combustion pressure and pressure rise rate directly tend to the stability.

3.4.2. Scavenging parameters
In the process of system operation, the inlet pressure will directly affect the system of scavenging state, in the condition of system voltage stability, the inlet pressure amplitude is in a relatively stable state, so also need to analyze the distribution of inlet pressure, will be to collect data, draw the corresponding graphics, and improve the integrity of the data sorting results. Based on the graph parameters, it can be seen that the distribution state of inlet pressure inside the system is basically consistent, and its maximum value should be controlled around 2.5bar [2]. And the piston moves along the top dead center, the system of the port will be in the closed state, and the scavenging cavity pressure will be on the rise of the state, the system in the process of expansion of piston expansion rate will also show a bigger difference, if the expansion of the piston speed faster, and the scavenging port will also is in a state of open early, and the scavenging efficiency will increase rapidly, And the residual exhaust gas coefficient in the cylinder will also drop, and fresh air will enter the cylinder, so as to create good conditions for the combustion of substances in the cylinder.

3.5. Cylinder working process
In addition to the related content mentioned above, it is also necessary to analyze the working process in the cylinder. In the specific analysis process, the engine can be regarded as an energy system. At this time, the input energy of the system mainly comes from the heat generated during combustion. In the specific combustion process, the mixed gases of high temperature and high pressure produced by the cylinder will smoothly convert the internal energy of the cylinder into the kinetic energy of piston operation. At this time, the heat energy generated in other forms will also leave the cylinder in the form of heat loss [3]. And cylinder expansion process, its reply cavity hydraulic energy and stored by the heat energy produced during burning, will be carried out on the piston, driven by the friction factors, there will be some friction damage, the hydraulic oil pressure is bigger, the system will direct discharge to the hydraulic pump cavity, then will also continue to store in the accumulator, waiting to use again, the recovery rate can be above 85%. In addition, in the process of system compression, it is also necessary to comprehensively consider the friction loss caused by the hydraulic energy generated by the compression accumulator in order to improve the stability of the system operation.

4. Stability analysis of hydraulic free piston engine

4.1. Nonlinear vibration analysis
In the application of hydraulic free piston engine, it belongs to the thermal-mechanical coupling system. In the specific research, the ordinary differential equations are used to analyze, and the numerical method is used to solve the obtained equations. Finally, the corresponding numerical solution is obtained by combining with the system cycle process, and the working characteristics of the system are obtained. At the same time, the numerical solution and the test results also maintain the relationship of mutual verification and complement, and in the quantitative analysis of dynamic characteristics, the numerical method used also occupies a relatively dominant position, to meet the relevant requirements of stable operation of the system. However, the numerical method also has strong limitations. In order to optimize the relevant contents of the numerical method, in-depth theoretical analysis will be carried out, and based on this, the establishment of nonlinear model will be completed to meet the requirements of the stable operation of the system [4].
4.2. Nonlinear model analysis

According to the application experience, quantitative laws cannot be obtained only by using qualitative analysis methods, and analytical solutions cannot be provided when numerical methods are applied. In order to make up for the shortcomings of these methods, analytical methods will be used to assist the expansion and solution of nonlinear models in the process of model analysis. When the analytical expression is calculated, the correlation between the energy parameters and the hydraulic parameters will be analyzed based on the mathematical solution perspective. In this way, the stability state can be scientifically evaluated to improve the rationality and reliability of the analysis results. In order to carry out optimization analysis of nonlinear systems and get reliable analytical solutions, a vibration model is generally built with the help of a physical model. The specific expression of the model is as follows: \( a = d - a' \), where \( a \) represents the standard coordinates after the transformation; \( d \) represents the distance between the cylinder head and the balancing system; \( a' \) represents the corresponding displacement coordinates in the physical model [5].

4.3. Stability and evaluation index

In the process of index evaluation, the evaluation indexes are as follows: (1) Eccentricity index, which is affected by parameters such as piston steady amplitude, piston balance position spacing, control chamber pressure, etc., and needs to be calculated by combining relevant formulas. (2) Scavenging limit index, which is mainly affected by parameters such as gas flow rate, air supply and scavenging time, can be calculated with the aid of formula expansion. (3) The energy input index, which is mainly affected by the steady vibration of the piston, can also be calculated by the formula. (4) To control the pressure stability index of the cavity, which involves steady amplitude, eccentric position, balance parameters, cylinder spacing, etc., can be calculated by formula expansion. (5) Working pressure index of pump chamber. After collecting experimental data for many times, the average value is calculated to get accurate calculation results [6].

5. Working stability control strategy of hydraulic free piston engine

5.1. Control of starting condition

In order to improve the stability of the starting condition, the matching oil circuit design can be completed on the existing basis, so that in the case of unsuccessful ignition, the excess hydraulic oil will be discharged through the oil circuit, thus reducing the recovery resistance. The specific design system is shown in Figure 4, in which the numerical matching relationship is as follows: 1- starting frequency valve; 2-return oil check valve; 3- Compression accumulator; 4- On/off valve; 5- main oil port; 6-return accumulator; 7-return control valve; 8- Supplement oil accumulator. In order to monitor the status of starting condition, it is also necessary to collect relevant information with the help of sensors, so that the dynamic adjustment of the system operation process can be carried out according to the collected information, so that the operating condition can be more stable and the relevant requirements of stable operation of the system can be met.
5.2. Fire condition control
In order to improve the control effect of the misfire condition, it is also necessary to do a good job of determining the misfire condition. In general, displacement signals of piston components will be used to evaluate, and reliable working condition data will be obtained with cylinder pressure data. And in signal control, also need to piston component position detection, the piston is located in the next check point, use the sensor to the related signal acquisition, which is then integrated into the control system, to evaluate the parameters, if the piston in lower dead center, the system into the work condition, need to open the conversely return switch valve, after its return to the check point, then the control valve will be closed, so that the system can re-enter the working condition [7].

5.3. Operating condition control
Under the influence of special frequency control mode, the working mode of the engine basically remains the same in the working process. In order to improve the system stability, it is necessary to optimize the working frequency of the engine and the working state of the injection system, so as to improve the working stability of the system. In the specific control process, it is also necessary to supervise the running state of TDC, use sensors to complete data collation, and dynamically adjust the operating parameters of the system in combination with the system frequency and the working state of piston components, so that it can be in a relatively stable operating state and improve the stability of the system working process [8].

6. Conclusion
To sum up, in the working process of hydraulic free piston engine, to ensure the stability of its working state is a very important application content. With the help of the established nonlinear model, the stability of the engine can be objectively evaluated, and the strategy to improve its stability can be formulated, which has a positive significance for extending the service life of the engine.

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