STRUCTURE RELIABILITY ANALYSIS AND EXPERIMENTAL VERIFICATION OF A NEW FREE PISTON EXPANDER

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ABSTRACT

A new free piston expander coupled with liner generator (FPE-LG) has been proposed in this paper, which can be used as a thermo-electric conversion device for organic Rankine cycle (ORC). Compared to other expanders, the free piston expander (FPE) seems to be the most suitable working component for small scale ORC system owing to good sealing, variable compress ratio and compact structure if the inlet/outlet control is worked out accurately. Thus, a physical prototype with a novel valve train has been manufactured, which is experimentally validated in an air test rig before it is integrated into whole ORC system.

In this paper, a general engineering methodology is adopted to analyze the structure reliability of the FPE valve train at different input frequencies. The dynamics simulation of the valve train is carried out via ADMAS software firstly, the obtained contact force results are set as boundary conditions of stress analysis. Based on elastic mechanics theory and finite element method, more precise calculation results about stress distribution on the valve train are obtained through transient structural module in ANSYS® Workbench V14.5. The results show that the maximal von Mises stress is 231.71MPa which mainly concentrate on the root of the valve slider. Although the maximal von Mises stress on the valve slider does not exceed its material allowable stress when the servomotor input frequency is 8Hz, the fluctuation of the stress is obvious, which leads to mechanical failure. FPE prototype with the valve train can realize the suction, expansion and discharge processes properly in the air test rig and can work stably in a relatively wide range of servomotor input frequency from 1Hz to 8Hz. The stress analysis and dynamics simulation results can provide a significant reference value for the mechanical performance optimization of the next generation FPE and further validation of the FPE-LG in the ORC system will be conducted in the near future.

1. INTRODUCTION

About one third of the energy which is produced by the automotive fuel combustion has been utilized, however, the majority has been wasted in the form of exhaust gases, cooling water and mechanical friction loss. Utilizing exhaust energy has recently become a more efficient and effective method by which to save energy and reduce emissions (Ou *et al*., 2013, Boretti, 2012). The organic Rankine cycle (ORC) system is not only a reliable and promising method for converting waste heat of vehicle exhaust into useful work but also a most likely industrialization technology (He *et al*., 2012).

As the core working part, the performance of expander has a direct influence on output power of automotive ORC system. Owing to small flow rate constraint and compact structure requirement, the traditional expanders such as the turbine, screw, scroll expanders have certain difficulties in application for the small scale automotive ORC system respectively. For instance, although the screw expander is widely used in ORC system, of which helix rotor surface with high accuracy must be manufactured by special equipment and tools (Wang *et al*., 2011). Furthermore, the screw expander can't reach the end pressure as high as reciprocating piston expander when the expansion process is completed (Gao *et al*., 2013). Due to large leakage under high pressure difference, the scroll expander has a low efficiency. Hence, very tight clearance design is required in order to achieve a satisfactory efficiency, which will make the manufacturing costs increased. As for the turbine expander, the rotating speed will exceed 200,000 to meet to this small flow rate, which is a great challenge associated with the reliability and mechanical strength. However, the free piston expander (FPE) is suitable to the condition of small flow and low output power (Han *et al*., 2014, Zhang *et al*., 2007). At present, studies of free piston expander mainly focus on the refrigeration field. No public reports about using free piston expander as working part for vehicle internal combustion engine (ICE) waste heat recovery has been seen in published literatures yet. Thus, free piston expander coupled with a liner generator has been proposed in this paper, which can be used as a thermo-electric conversion device in vehicle ICE waste heat recovery. Moreover, the FPE-LG prototype is preliminary validated in the air test rig under low intake pressure and steam flow rate condition before it is integrated into the whole ORC system.

2. DESCRIPTION OF THE FPE-LG PROTOTYPE

2.1 The system description of free piston expander coupled with liner generator (FPE-LG)

The thermo-electric conversion components in conventional automotive ORC system consists of independent expander and generator, which need more space for installation and make the ORC system very difficult to application in the vehicle. The FPE-LG unit can be used as a substitute for thermo-electric conversion components in the small scale automotive ORC system owing to compact structure. The basic concept presents in this work is illustrates in Fig.1.

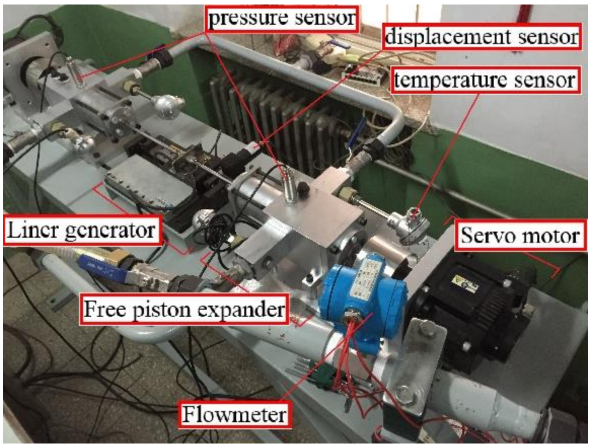


Figure 1: System diagram of FPE-LG

As shown in Fig.1, FPE-LG unit is mainly composed of four components: expander, liner generator, servomotor, measurement and control system. Compared to the opposed arrangement form with two free piston expanders, the piston returning of an independent free piston expander needs an additional return spring what will decrease the reliability in working process. Furthermore, electric energy production by the liner generator need reciprocating movement of the mover. Thus, the former scheme is adopted. Both the output ends of the two opposed FPEs are jointed together with the mover of the liner generator through two flexible joints, and enable the mover to free reciprocate without additional return springs under the support of stator which is fixed on the test-bed. Working principle of the FPE-LG is discussed in detail in the following section.

2.2 Structure layout of free piston expander

During the concept design phase of the prototype, what we mainly focus on is the total electric energy production of liner generator which is decided by piston velocity of FPE according to Faraday's electromagnetic induction law. While the pressure and flow rate of the working fluid in the small scale ORC system have a significant influence on the piston velocity of FPE. Thus, it is very important to select appropriate structure parameters in order to satisfy these design requirements. Subsequently, the diameters of the expander cylinder and the stroke are calculated according to the assumed compression ratio. Moreover, the important factors which are mentioned above have been taken into consideration overall. The final geometric parameters of the FPE are determined as shown in Table.1.

Table 1: Structure parameters of free piston expander

Items	Value	Units
Cylinder bore	80	mm
Working frequency	1-8	Hz
Stroke	102	mm
Piston rod diameter	10	mm
Compression ratio	8	
Intake/exhaust port diameter	20	mm

Fig.2 shows the structure of the free piston expander. The FPE mainly includes following components: cylinder head, piston group, cylinder, valve seat, cylinder block, valve train, valve sleeve, fixed plate, cover, guide sleeve, input shaft. Simultaneously, the output end of a 200V servomotor is connected to input shaft of the expander with a flexible coupling joint which can ensure alignment of center line. Thus, working fluid inflow and outflow of the FPE can be adjusted via the valve train which movement is controlled by the servomotor. In order to reduce the loss of friction, the closed space between the cover and fixed plate is filled with lubricating oil which can be added through a small hole on the cover. We select aluminum alloy for constituting the moving parts including valve and piston while the other main parts are constituted with 304 stainless steel, since aluminum alloy has high-strength which is used generally in ICE piston design, it can bear the high pressure and temperature in ORC system and maintain its mechanical property in these conditions while 304 stainless steel has good resistance to corrosion. Owing to the mechanical wear between the piston group and cylinder head, a guide sleeve constituted with aluminum bronze is placed in the cylinder head which can improve the service life of piston rod and meet the high precision demand of the piston group installed.

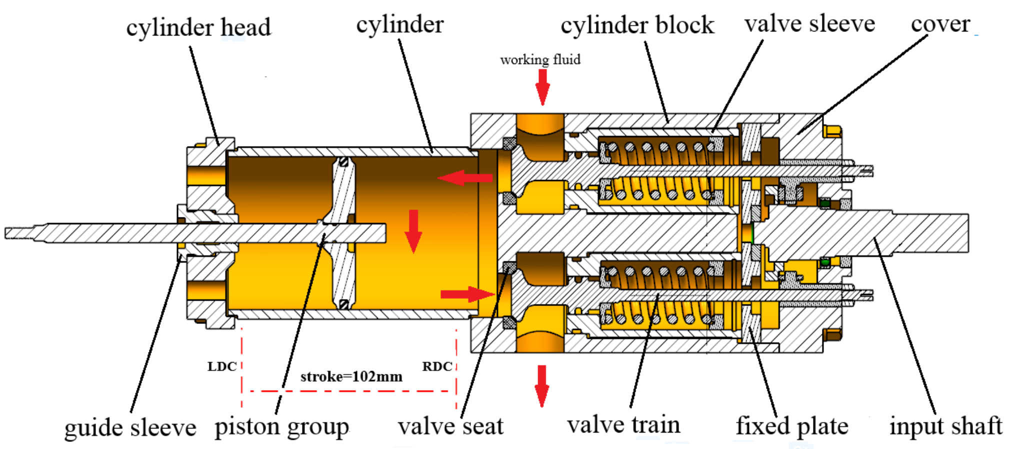
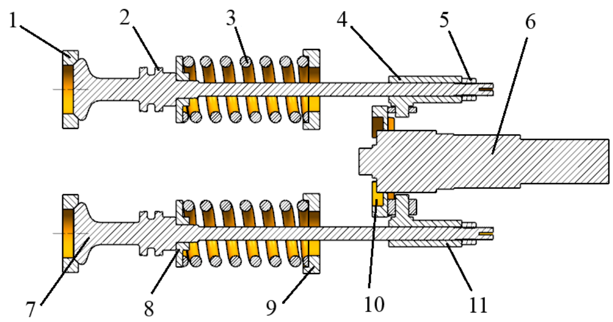


Figure 2: Structure diagram of free piston expander

Based on the description about main structure of the free piston expander and selection of key parts above, the working process of the FPE-LG prototype can be simply described as following: firstly, two servomotors are set to certain phase difference before the FPE-LG operates, which can ensure the inlet valve of expander on one side opens while the outlet valve on other side closes. Taking the expander on the right side (as shown in Fig.2) as an example, the exhaust gas exchanges heat with the organic working fluid in the evaporator when ORC system works. Meanwhile the organic working fluid turns into high-temperature and high-pressure gas, which is injected into the expander intake port and then enters into the expander cylinder when the inlet valve opens, driving the piston to the LDC. Simultaneously, the outlet valve of the left expander opens which is controlled by another servomotor and the in-cylinder pressure is lower than the right side. So the piston is pushed to the RDC under the action of force produced by the right expander. In this process, the liner generator mover can move together with expander piston groups, cutting the magnetic induction lines to produce electric energy.

2.3 The expander inlet/outlet control method

The free piston expander seems to be the most suitable thermal-power conversion component for small scale ORC system if the inlet/outlet control is carried out successfully, since it has the greatest potential for practical application owing to the good sealing, less mechanical loss and simple structure. In fact, the development of the free piston concept at the TU Dresden seems to be the most promising one up till now, because the efficiency was reported to approach 50% and the prototype expander was verified to be feasible. The electronically controlled valve is abandoned owing to the high cost and complex control system. Thus, a novel mechanical valve train has been created for the FPE in this paper and a full scaled CAD model of the valve train which is built via CATIA V5R21® is prepared for the subsequent analyses, as shown in Fig.3.



1-valve seat 2-outlet valve 3-valve spring 4-outlet valve slider 5-nut
6-input shaft 7-inlet valve 8-bearing disc A 9-bearing disc B 10-cam plate
11-inlet valve slider

Figure 3: Structure diagram of FPE valve train

The structure of the FPE valve train is illustrated in Fig.3. It is mainly composed of several parts: valve seat, valve spring, cam plate, inlet/outlet valve slider, input shaft, inlet/outlet valve, bearing disc A and B. The cam plate is processed into stepped shape with a height difference of 3 millimeter. The surface of upward and downward position is processed into arc surface in order to reduce the resistance of the valve opening and closing. The valve spring with a pre-compressing quantity of 5.5 millimeter is fixed between bearing disc A and B when the expander is assembled. An axial hole through the center of valve slider is manufactured which can be used to fix the valve with a nut. And the gap between bearing disc B and cam plate can be adjusted by changing the mounting position of bearing disc B after the valve train is assembled into the FPE cylinder block. Through this kind of design approach, the valve slider can be compressed on the cam plate. Thus, the valve opening and closing which is driven through the rotating movement of the cam plate can be achieved.

Considering that the reliability and durability of the valve train is mainly determined by spring load, natural frequency, fatigue resistance and relaxation properties, 55CrSi has been selected for constituting the mechanical spring of the valve train owing to wide applications in the field of high stress spring and excellent mechanical character which can insure the air tightness at the same time. According to the design parameters of the mechanical spring, as shown in Table 2, spring stiffness (*f*) can be calculated with following equation:

$$f = \frac{G \cdot d^4}{8 \cdot D^3 \cdot n} \tag{1}$$

Table 2: Mechanical spring parameters

Parameters	Mean	Value	Units
G	Shearing modulus of elasticity	8×10^4	N/mm^2
d	Spring diameter	25	mm
D	Wire diameter	5	mm
n	Effective number of turns	5.5	-
f	Stiffness	72.7	N/mm
L	Spring relaxation length	67	mm
c	damping	0.66E-003	N·s/mm

3. DYNAMICS SIMULATION OF THE FPE VALVE TRAIN

3.1 Dynamics simulation model description

The irregular contact surface between cam plate and valve slider will cause a serious problem of calculation convergence in the process of stress analysis. Owing to the diffculty of the nolinear problem in transient structural solution, we adopt a general engineering methodology. Firstly the dynamics simulation is carried out via ADMAS software, which is a professional mechanical dynamics simulation software. Then the contact force simulation results between the valve silders and cam plate are exported and be set as stress analysis boundary conditions in transient structural module of ANSYS® Workbench V14.5. Furthermore, it is also convenient to analyze the valve train movement rule and the design parameters of cam plate profile through ADMAS.

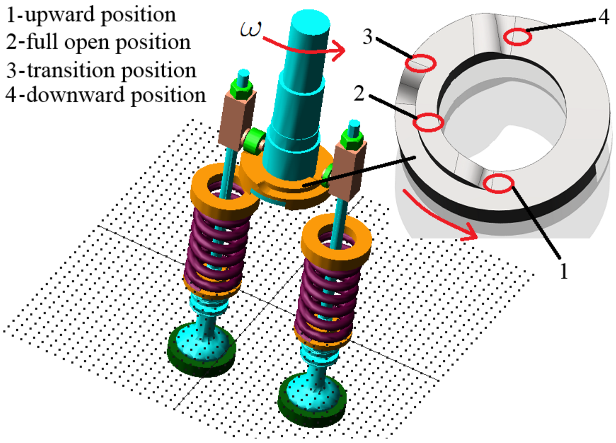


Figure 4: Dynamics simulation model of the valve train

As shown in Fig.4, aim to get the force conditions in the contact location between valve sliders and cam plate, the CAD model we prepared has been imported into the ADMAS. And then, constraints and loads are added according to the true motion. In order to obtain precise results, the spring, valve sliders and valves are set as flexible parts which are divided into suitable mesh, while the rest are set as rigid parts. Simutaneously, the time of the cam plate rotates a cycle is defined as the end time of simulation in order to observe the change of force more clearly, while the simulation steps are defined to one thousand which can ensure the accuracy of dynamics simulation results.

3.2 Analysis of the simulation results and boundary conditions extraction

Force conditions between the inlet/outlet valve sliders and cam plate at different servomotor input frequencies is analyzed. We select 2Hz, 5Hz, 8Hz, 10Hz as input simulation variables to prove the reliability of the valve train at design frequency.

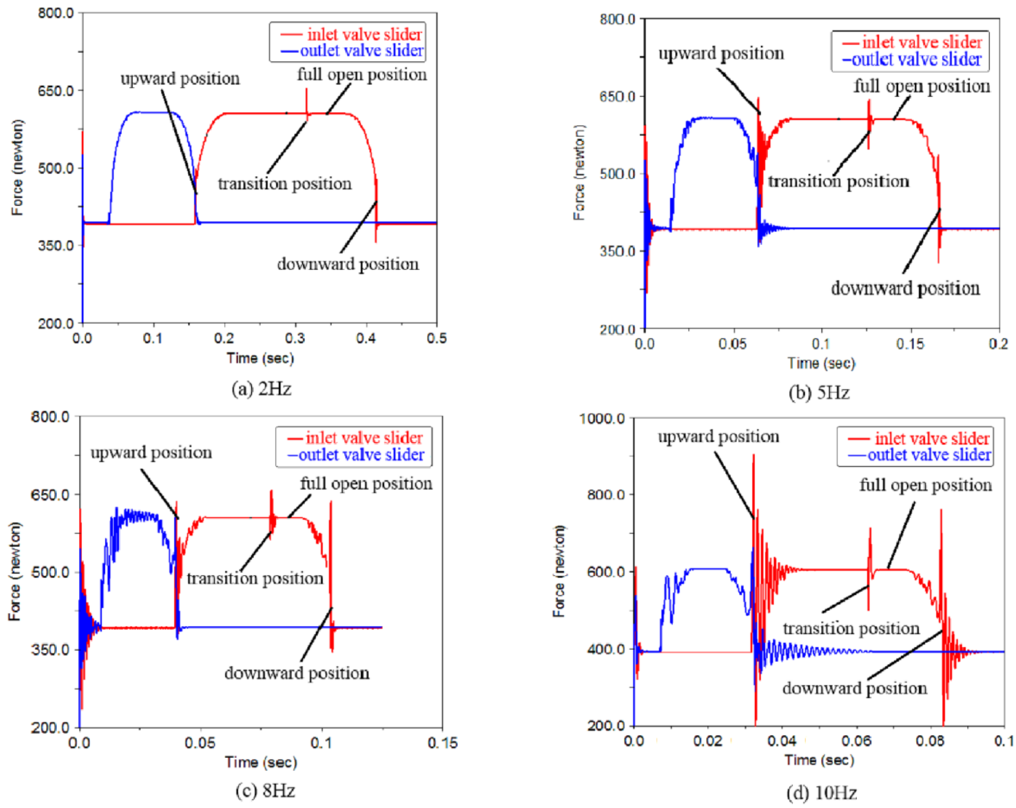


Figure 5: Total contact force of valve sliders at different servomotor input frequencies

Fig.5 shows the total contact force comparisons between the inlet and outlet valve slider at different input frequencies. The sudden change of contact force on inlet valve slider increased significantly with improvement of the servomotor input frequencies when it reaches the upward and downward positon, while the change rule of outlet valve slider is not obvious at low input frequency. There is hardly any sudden change of the force in the inlet valve opening and closing process in Fig.5(a), however, as we can see in Fig.5(b) (c) (d) the fluctuating intensities and the magnitudes of the force changes obviously. Simultaneously, a sudden change of contact force occurred at the transition positon owing to the sudden decreasing of the contact surface between inlet valve slider and cam plate. However, the contact surface between outlet valve slider and cam plate is constant, so the variation of contact force between the outlet valve slider and cam plate at the transition position is very different from it. Meanwhile, both contact force of the inlet and outlet valve slider has no significant change at the full open position. Then, the force data of inlet/outlet valve sliders in three coordinate directions is exported, which can be set as the force load in following stress analysis.

4. FINITE ELEMENT MODLE OF THE FPE VALVE TRAIN

Based on analysis of the simulation results above, the left side where inlet valve is settled as shown in Fig.4 is taken as main research object owing to the complexity of the contact force change. The finite element (FE) model of the valve train used in the numerical analysis is constructed, the assembled finite element model includes inlet valve, valve spring, inlet valve slider, nut, circular bearing disc A and B, as shown in Fig.6.

In order to precisely simulate the real contact and load conditions in stress analysis, the simplified model is meshed using SOLID187, a higher order three-dimensional solid element, which has a quadratic displacement behavior and well suited to model irregular meshes. The element is defined by 10 nodes having three transitional DOF at each node. The valve train FE model has 319795 elements and 484079 nodes.

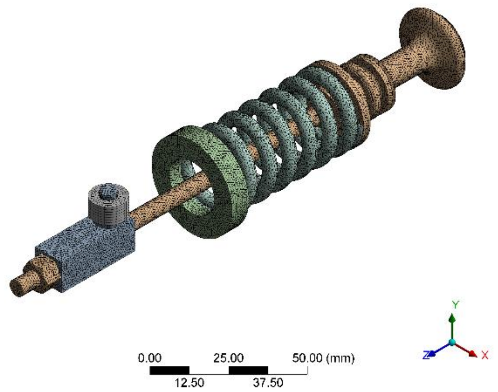


Figure. 6: Finite element model of the valve train

4.1 simplification of boundary conditions and imposing load

In order to ensure convergence of calculation, the boundary conditions such as force and displacement of each part or part contacts must be simplified according to actual conditions before the solution program of FE model has been carried out.

Based on the actual working conditions, an equivalent intake pressure which is imposed on the inlet valve head has been ignored. The total friction of contact portions has much less influence on the calculation results in the design conditions owing to splash lubrication. Then, the contact force of inlet valve slider in three coordinate directions which is obtained via ADMAS is imported into transient structural module as calculation boundary. Considering that it is approximately liner contact between the inlet valve slider and cam plate, main load is defined to nodal force which magnitude depends on the dynamic simulation results. Completely bonded contact is assigned to the interface between components. A displacement constraint which is limited the X, Y directions and free the Z direction is applied to four profiles of the valve slider and a fix constraint is assigned to the cylindrical surface of the bearing disc B. Finally, an equivalent spring contact is assigned to the contact surface between two bearing discs which stiffness, damping, preload is defined to 72N/mm, 0.66E-003Ns/mm and 400N according to the calculation results in section 2.3, respectively.

4.2 Experimental validated of FPE-LG in air test rig

In order to validate the correctness of working principle of the expander and the valve train, an air test rig has been set up. As shown in Fig.7, it includes high pressure air compressor, air receiver, connecting pipe, FPE-LG, acquisition system. Furthermore, test of the valve train in actual working conditions is conducted to validate the results of stress simulation, which is discussed in detail in the following section.

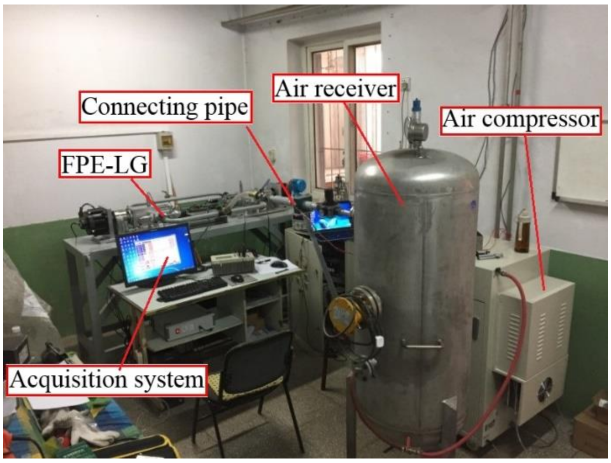


Figure. 7: FPE-LG test bench

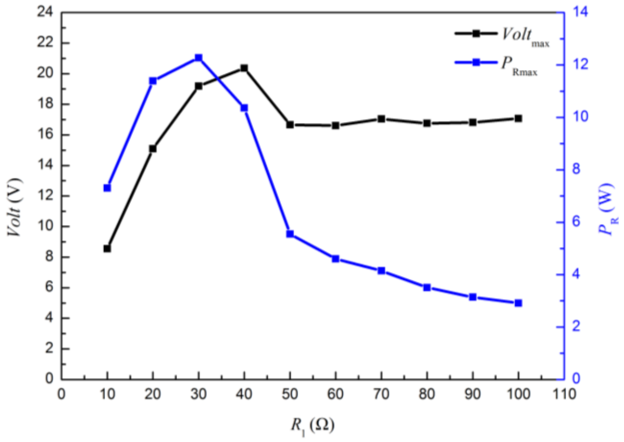


Figure. 8: Load peak voltage and peak power for different load resistance

In order to assess the thermoelectric conversion capacity of the FPE-LG, preliminary experiment is carried out at a certain condition, which intake pressure, input frequency, external load resistance is 0.2MPa, 1.5Hz and 10Ω-100Ω respectively. As illustrated in Fig.8, the maximum transient voltage is 20.4V when the external load resistance value is 40Ω. The maximum output power is 12.3W when the external load resistance value is 30Ω according to the Ohm's law. Since the compressed air is selected as working fluid in this pneumatic test, the working pressure and temperature are lower than conventional ORC system. However, the transient maximum output power of FPE-LG is considerable. More experiments about other variable factors includes intake pressure, input frequency, evaporating temperature will be conducted when the FPE-LG is integrated into a small scale ORC system.

The FPE-LG prototype can operated stably at different servomotor input frequencies from 1Hz to 8Hz. The maximal pressure in cylinder can reach 5 bar. Although the FPE-LG prototype can operate at a higher input frequency and pressure, we don't further improve it since the collision between piston and cylinder head increases obviously with input frequency improving.

5. ANALYSIS OF SIMULATION RESULTS

The prototype can operate steadily at different input frequencies in the air test rig. However, crack of the inlet valve slider mainly originates from the same region after long time running, which is marked with A in Fig.9.

Figure 9: Actual failure region of the inlet valve slider

FE analyses results illustrates that the root of inlet valve slider is subjected to stress concentration which make it easily failure region and can cause a premature failure problem. This is consistent with the actual damage conditions. Owing to high speed and frequent collision with the cam plate, a large quantities of heat is generated through friction, which can also reduce the serve life of the inlet valve slider.

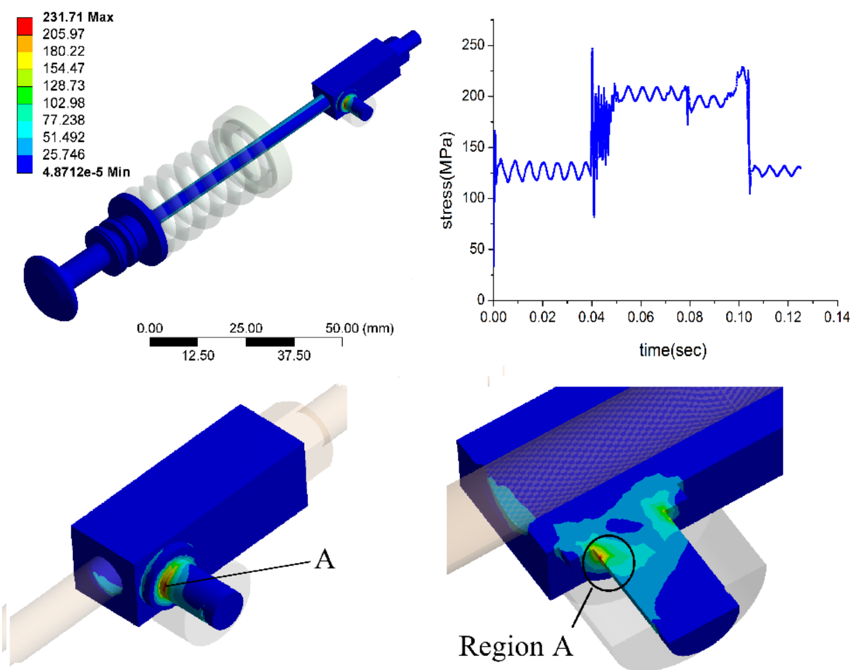


Figure 10: Equivalent von Mises stress (MPa) distribution on the inlet valve slider

Fig.10 shows equivalent von Mises stress distribution obtained from the FE analysis when the servomotor input frequency is 8Hz which is the maximum value in actual test conditions. It can be seen that the maximum von Mises stress is 231.71Mpa which mainly concentrates on the root of inlet valve slider when it moves from upward position to full open position. Simultaneously, the fluctuation of the von Mises stress is obvious in one working cycle. The results are agreement with actual situations. The maximum stress is meet limit yield of material which is selected to constitute the valve slider. However, the stress in this area (marked with A) is close to the mechanical strength of the material, which indicates that the region is a critical area and prone to be failed. Enhancement of the fatigue life of the inlet valve slider is dependent on the decreases of the stress concentration. Hence, adding a fillet to the root of inlet valve slider and taking heat treatment are both the effective methods to eliminate the stress concentration. Because of the exact value of stress distribution on the root of valve slider is difficult to measure in practice, the proposed method of analyzing the failure of valve slider, which takes into account of several key position, is predictive and applicable.

6. CONCLUSIONS

In this paper, an engineering methodology is adopted to analyze the structure reliability of the FPE valve train. And experimentally validated of FPE-LG in an air test rig is conducted before it is integrated into whole ORC system. The main conclusions can be drawn as follows:

- The results of the stress analysis indicated that the region of stress concentration on the inlet valve slider is in coincidence with the real failure areas. The maximum value of the von stress is 231.71MPa in a working cycle. The stress concentration and fluctuation are two main factors which strongly affects the structural reliability of the valve train. The methodology is feasible and low-cost in the prototype design. And the mechanical damage of the operated prototype indicates that FPE can't work normally when it deviated from the analysis results in this paper.
- The FPE-LG with the novel valve train was validated in the air test system. The results shows that the FPE-LG can operate in a wide range of input frequencies from 1Hz to 8Hz which reveals that the inlet/outlet control scheme is feasible. Furthermore, the pressure in cylinder can reach 5 bar. The FPE-LG prototype described in this work is shown to be successful in meeting its design goals.
- Further experimental validation about the FPE-LG will be conducted in a miniature ORC system in near future.

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