Reliability Improvement of the Piston Compressor in FD-21 Free-piston Shock Tunnel

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Abstract

The FD-21 free-piston shock tunnel (FD-21FPST) is a 2m-scale high enthalpy shock tunnel built in China Academy of Aerospace Aerodynamics (CAAA). The piston compressor is the core of the FD-21FPST, which mainly contains the high-pressure gas chamber, the free-piston, the compression tube, the buffer mechanism and the main diaphragm station. As the core component of energy transfer, the stable operation of the free-piston is the guarantee of the stability of the wind tunnel. Since FD-21FPST was built, a series of technical improvement work has been done to improve the reliability of piston compressor, and ensure the safe operation of the FD-21FPST in the past year.

1 Introduction

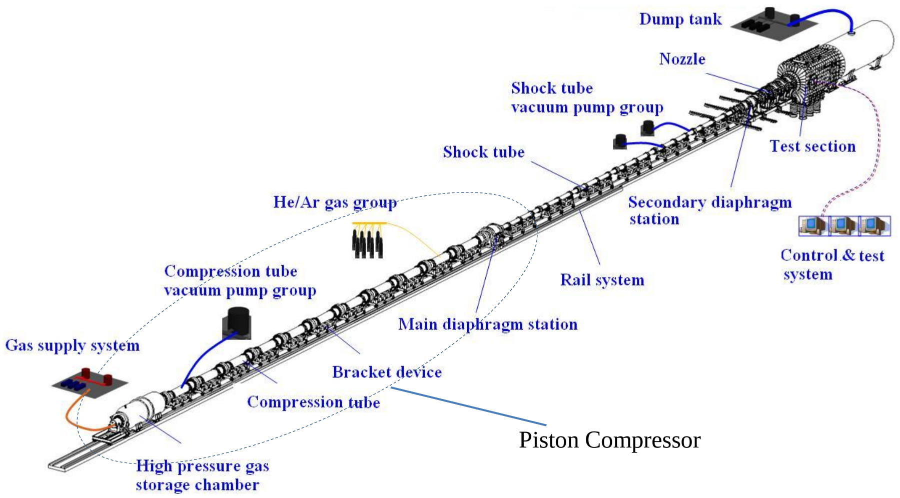


Figure 1: Schematic diagram of the FD-21FPST.

As shown in Figure 1, the FD-21 free-piston shock tunnel (FD-21FPST) is a 2m-scale high enthalpy shock tunnel built in China Academy of Aerospace Aerodynamics (CAAA). It obtains high temperature and high pressure test gas through two-stage compression drive mode, and satisfies the requirement of high enthalpy test condition by relatively inexpensive and safe way. The nozzle aperture 1.2~2m, the nozzle chamber total temperature reaches the 2000~8000K, both the high enthalpy and the long time kinds of wind tunnel operation mode, the simulation ability is the leading in the domestic. It mainly carries on the research of the high temperature real gas effect, the propulsion integration and the scramjet performance research, the high Mach number aerodynamic test and so many other experiments of the high enthalpy aerodynamic.

The core of the FD-21 high-energy shock wind tunnel is the piston compressor, which is composed of a high-pressure gas chamber, a compression tube, a free piston, a stop mechanism and a main diaphragm section. The piston compressor is used to form a first-stage driving device, which compresses the gas-driven gases, such as Helium/Argon gas, in the compressed tube into a high temperature and high pressure state, and forms a high intensity shock wave required by a secondary drive.

In the tunnel, free-piston which is running in the piston compressor is the core component of energy transfer. The energy is converted to the kinetic energy of the free-piston form the high-pressure air in high pressure gas storage chamber, by pushing the free-piston along the compressed tube in high speed. And then, the free-piston compresses the drive gas in front of itself, converts the kinetic energy to the internal energy of the drive gas which reaches high temperature and high pressure. A strong shock wave occurs when the main diaphragm in the main film mechanism is broken by the drive gas. The shock wave moves forward in the shock tube, and heats the test gas to a high temperature and high pressure state of the test design. Through this process, the energy is converted into the internal power of the test gas. The test gas is accelerated through the nozzle to the fluid with super high speed, which flows through the test model and completes the experiment in the test section. In the process, the movement of the free piston needs to be guaranteed to operate stably and safely, in order to transmit the maximum energy to the test gas. Otherwise, the large residual energy of the free-piston will be released by damaging itself and other devices.

In the wind tunnels with same operating principle, such as Hiest, HEG, etc., precise control of piston operation and other methods were used to improve the stability of the wind tunnel operation. Because of the inconsistent principle of piston launcher, the overall stability of the piston compressor is improved by using the control of the performance stability of the launcher, improving the structure strength of the piston body, enhance the buffering capacity of the buffer mechanism, the accurate measurement of the film breaking pressure of the main diaphragm, the accurate measurement of the whole process data of the piston compressor and optimizing the piston operation strategy. It solves the problem that the wind tunnel piston rupture and the diaphragm pressure of the main membrane affect the safety of the Wind tunnel operation, which greatly improves the stability of the FD-21FPST operation.

2 Reliability Improvement of Equipment

2.1 Stability Control of Piston Launcher

The piston launcher of FD-21FPST is a kind of self-driven universal rapid launching mechanism, which is set up in the high-pressure gas chamber. Its launch performance is independent of the free-piston's configuration. It can launch the free-piston of various structures with high pressure launch efficiency. The operating stability of the piston launcher includes the stability and reliability of the launch action and the repeatability of the launch efficiency under the same pressure, which is the foundation of stable operation of wind tunnel. As shown in Figure 2, the core structure of the launcher is a piston valve driven by the pressure difference of the front and back chamber, which can be used to control the launch motion reliably by inflating and degassing the back chamber of the piston just rely on an inflatable valve and a launch valve.

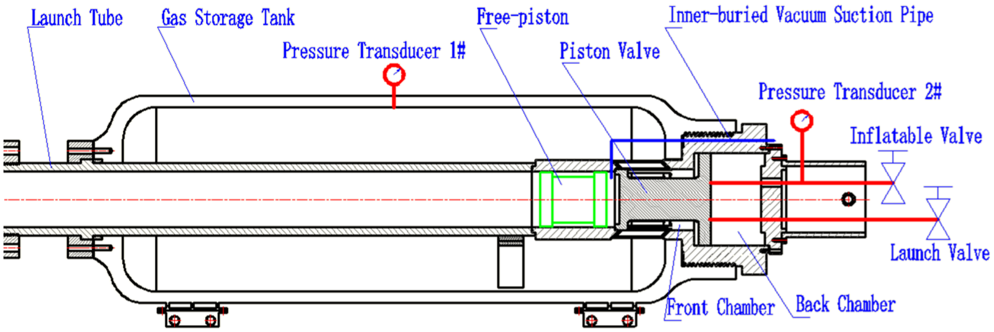


Figure 2: Structure chart of piston launcher.

In order to achieve high enthalpy state in high-energy pulse wind tunnel, the air in the compressed tube needs to be replaced by Helium/Argon gas. In the process of vacuum pumping, a small amount of air in the rear of the free piston will push the piston forward from the beginning of the launch tube, resulting in a certain displacement and a large change in the launch efficiency. In the launcher, a vacuum is first pumped for space behind the free-piston by the inner-buried vacuum suction pipe, which ensures the stable position of the free-piston in the beginning of the launch tube, and guarantees the stability of the launch efficiency. In the process of inflating the gas storage tank of the launching mechanism, the pressure of the back chamber of the piston valve will be tightly pressed on the sealing structure of the launch tube’s end face. The higher of the launch pressure, the larger of the sealing force is, which formed the high pressure self-tightness sealing effect. It ensures that when the high launch pressure is required, high-pressure air will not leak into launch tube before the launch action, which avoids the false-launch action.

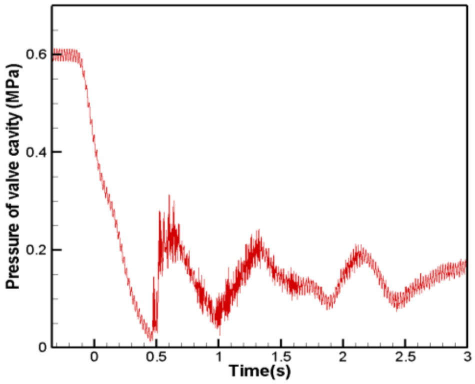


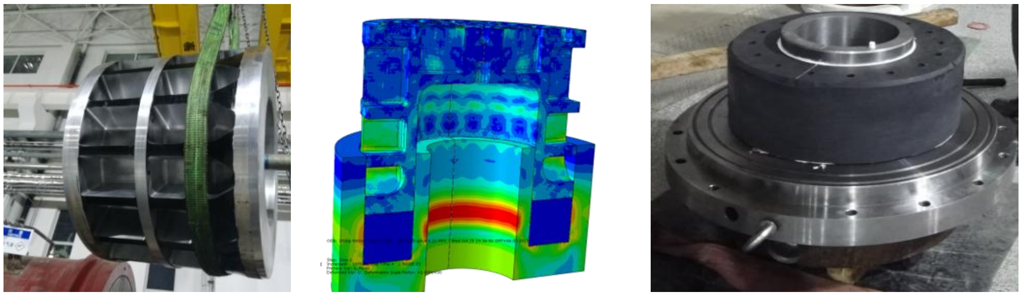
Figure 3: The change process of the piston pressure in the back chamber

As shown in Figure 2, two pressure transducers are used to measure the pressure of the front chamber and the back chamber of the piston valve respectively. By measuring the pressure change process of the back chamber of the piston valve, which is shown in Figure 3, the running state of the piston valve can be analyzed and determined to ensure the consistency of the emission efficiency under the same pressure. It can not only monitor the running state of launching mechanism, but also confirm the stability of launch efficiency before the wind tunnel test starts.

2.2 Design and Use of High-strength Piston and Reliable Buffer Mechanism

The piston operation control in the free piston shock tunnel is the key to ensure the stable operation of the wind tunnel. However, the accidental factors in the test will cause the free piston to reach the end of the compression tube at a speed which is too fast to slow down and impact the main diaphragm section with a force which is too large to ensure safety. Therefore, under the required mass, the structural strength of the free-piston body should be as high as possible, and it is an important method to improve the stability of the wind tunnel operation. At the same time, it is necessary to set up buffer mechanism with strong buffering ability to ensure the safety of wind tunnel equipment.

In order to solve the problem of insufficient pressure capacity of the original free-piston, the piston with multiple outer rib structure is designed, as shown in Figure 4(a), and the pressure and impact resistance are improved greatly. In the process of design, the motion process of free piston entering the buffer mechanism is calculated by FEM modeling, and a picture of calculating the stress distribution is shown in Figure 4(b). According to the calculation results, the piston structure and buffer structure are optimized to ensure the safety and reliability of the piston in the buffer mechanism. When the open air buffer cavity is used as the main buffer structure, there is a problem of insufficient buffering performance for twice. The design uses the open hole rubber ring as the main cushion structure, as shown in Figure 4(c), and the long buffer distance and the high rubber strength are taken into account. The strength and overall impact resistance of the new designed piston are validated by several tests, which ensure the stable operation of the high-energy pulse wind tunnel.



(a) (b) (c)

Figure 4: High-strength piston and reliable buffer mechanism

2.3 Optimized the Diaphragm Dynamic Breaking Test System

The main diaphragm is clamped in the main diaphragm section, and it is an important structure for separating the compression tube and the shock tube. The rupture pressure of main diaphragm directly affects the movement process of the free-piston and the performance of the test-airflow. Therefore, the accurate measurement of the rupture pressure of the main diaphragm is the prerequisite to ensure the stable operation of the free-piston. Because of the large difference of the static pressure and the dynamic rupture pressure of the diaphragm, it is necessary to set up the diaphragm dynamic breaking pressure detection mechanism which can reproduce the actual operation of the piston compressor.

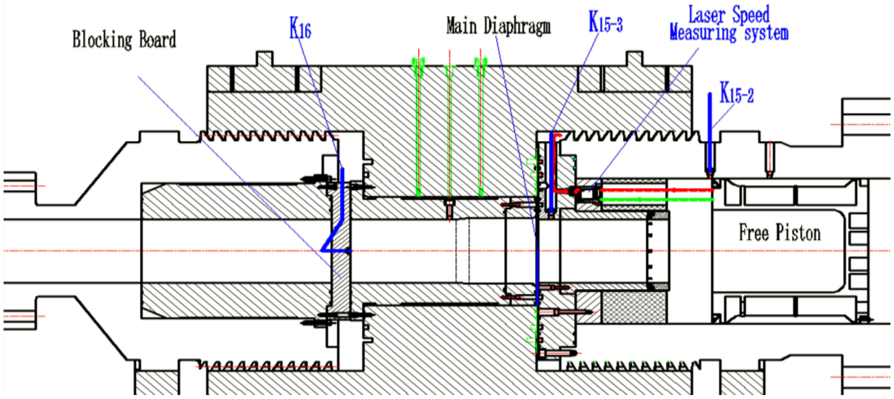
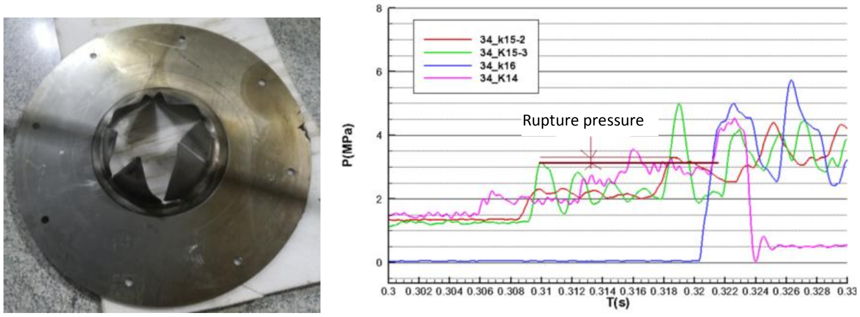


Figure 5: Dynamic breaking pressure test system for diaphragm



(a) (b)

Figure 6: Broken diaphragm and the test data

A diaphragm breaking pressure dynamic test system is designed to measure the rupture pressure by using the real running process and operating parameters to ensure the safety of the piston. As shown in Figure 5, a blocking board is arranged on the shock tube side of the main diaphragm section, and the main diaphragm is arranged on the compression tube. A closed space is formed between the blocking plate and the diaphragm. The pressure transducer K15-2 is installed at the end of the compression tube to measure the P4 when the diaphragm is breaking. The pressure transducer K15-3 is installed at the upstream position close to the diaphragm to measure the breaking pressure. The pressure transducer K16 is installed on the front end face of the blocking board to determine the exact time of the diaphragm rupture.

In order to maintain the stability of the membrane pressure, the main diaphragm is designed as an equal thickness flat plate with uniform star grooves. After the test, the opening shape of the main diaphragm is shown in Figure 6(a). The measurement data of a diaphragm breaking test is shown in the Figure 6(b). The rupture time of the main diaphragm is analyzed by using the process data and shock velocity of the pressure transducer K16. According to the rupture time and the pressure process data of K15-2 and K15-3, the rupture pressure and equivalent pressure P4 of the main diaphragm are analyzed.

2.4 Set up an Accurate Piston Measurement System

The running process of the free-piston in the compression tube is the core process of the FD-21FPST. The accurate measurement for change process of the velocity and the pressure during the free-piston movement is the basis of analyzing the launch efficiency, detecting the wear state of the piston and optimizing the operation parameters of the wind tunnel. As shown in Figure 7, the accurate piston measurement system includes the photoelectric measuring system, the laser speed measuring system, the distributed pressure measurement system, the acquisition system and the analysis system.

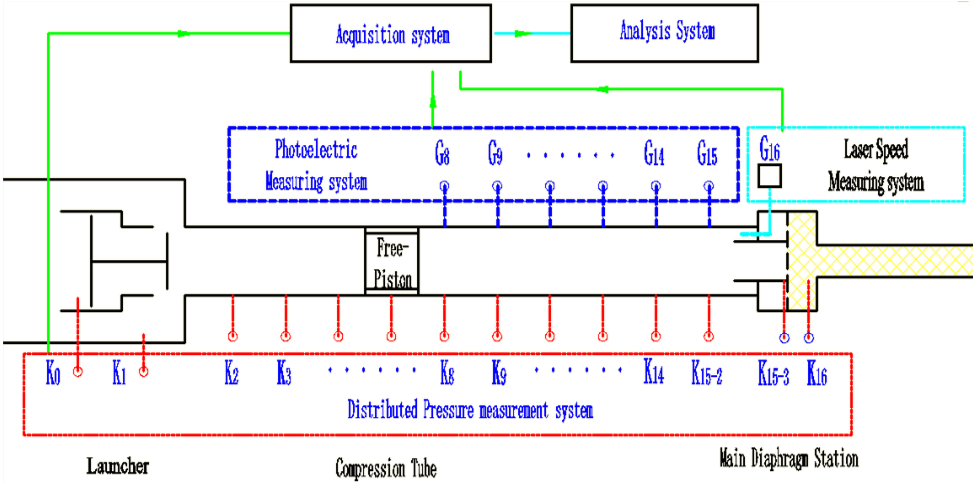


Figure 7: Schematic diagram of the accurate piston measurement system

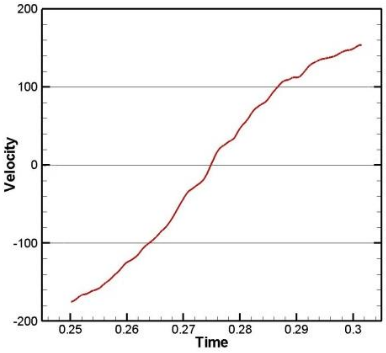


Figure 8: The change process of the piston velocity in the 5m range of the compression tube end

The photoelectric measurement system is composed of a series of photoelectric sensors which are distributed along the compressed tube, and it is used to measure the moment and speed of the free-piston when it is passing through each measuring point. In order to improve the accuracy of velocity measurement for free-piston in 5 meters at the end of compression tube and solve the problem that photoelectric sensor can't withstand high temperature and high pressure airflow, the laser speed measuring system is set up in the buffer mechanism, as shown in Figure 5. A series of pressure sensors distributed along the compressed tube constitute the distributed pressure measurement system and they can measure the pressure change process of the piston compressor during the process of wind tunnel operation.

The Figure 8 shows the velocity change process of free-piston at the end of the compression tube in a diaphragm breaking pressure dynamic test. This data can be used to modify the simulation program of the piston compressor.

3 Optimization of piston operation strategy

In the theoretical calculation of wind tunnel operation, a free piston operation simulation program is established. The piston running process and pressure change process under the ideal condition are calculated under wind tunnel operating parameters. According to the process of free piston movement and pressure change in the actual test, the correction coefficient in the theoretical analysis model is adjusted to obtain the simulation program which can simulate the wind tunnel running process accurately. The original calculated value of the free piston end velocity and the modified result are shown in Figure 9. It shows that the modified result is in good accordance with the actual piston speed.

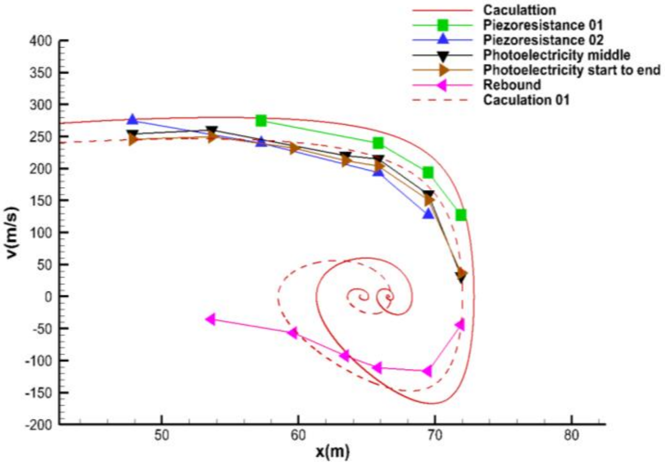


Figure 9: The original calculated value of the free piston end velocity theory and the modified result

With the accurate theoretical simulation program, we optimized the free-piston operation strategy, which enabled the free-piston to reach the end of the compression tube at a very low speed. The optimized operation strategy enables the free-piston to have a more stable and safe operating performance.

4 Conclusion

Through a series of improvement situation, the piston compressor can operate reliable and safe. This is the foundation of the running and the further improvement for the FD-21FPST.

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