Design and Research of Pneumatic Sensor for Nuclear Fuel Reprocessing Equipment

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Abstract. In the radiation environment, the traditional electronic trigger sensor will receive the interference of radiation, resulting in inaccurate signal transmission, easy to generate wrong signals and cause misoperation, there are security risks. Therefore, this paper studies a kind of pneumatic sensor used to detect the position trigger of the silo, and has the function of rapid disassembly and assembly. In the radiation environment, the robot can be used to quickly disassemble and retrieve the sensor, so as to facilitate the maintenance and repair of the sensor. The simulation design of mechanical structure, trigger device and air path system in pneumatic sensor is emphasized. In the radioactive source environment, air pressure signal is used instead of electrical signal to detect the equipment in place, which ensures the signal safety of the equipment.

Keywords: Pneumatic sensor, fast disassembly, high precision, simulation of aerodynamic characteristics

1 Introduction

The Three Mile Island nuclear accident in 1978, Chernobyl nuclear accident in 1986 and Fukushima nuclear accident in 2011 cast a huge shadow on the peaceful use of nuclear energy by mankind [1]. Therefore, the nuclear industry is an extremely important industry, and the technology and equipment involved in it have a profound impact on the development and progress of mankind. Pneumatic sensors are one of the crucial instruments in the nuclear industry [2][3]. Pneumatic sensor is an instrument used to detect gas pressure, flow rate and other parameters. It is widely used in nuclear power plants, nuclear reactors and nuclear fuel processing plants and other nuclear industry fields to monitor, control and protect nuclear facilities [4][5]. Therefore, the research and development of high precision and high reliability pneumatic sensor technology for nuclear industry is of great significance to ensure the safety of nuclear industry, improve work efficiency and reduce accident risk.

2 Overall design of pneumatic sensor

The pneumatic sensor is installed on the mechanical equipment in the hot room, which is used to detect the position state of the moving parts and feed back the position signal to the control system. The main structure is composed of trigger mechanism, valve body, quick joint and shell. The tail of the pneumatic sensor is connected to the air pipe, and the air path connected to the pneumatic sensor is in a closed state when it is not triggered. When the trigger mechanism of the pneumatic sensor is triggered by the trigger block on the measured mechanism, the pressure relief in the valve body of the pneumatic sensor causes the conduction of the connected air path and the pressure drop. The pressure drop is converted into an electrical signal by the pressure transmitter outside the thermal room and fed back to the control system.

The pneumatic sensor is triggered by the linear movement of the electric push rod of the equipment. The trapezoidal slide block of the head of the electric push rod moves, and the trigger rod of the pneumatic sensor is jacked up. The trigger ball of the check valve is jacked up inside the trigger rod, so that the air path part is connected with the environment, and the pressure drop is generated, which is collected by the pressure transmitter. The overall gas path schematic design scheme is shown in Figure 1.

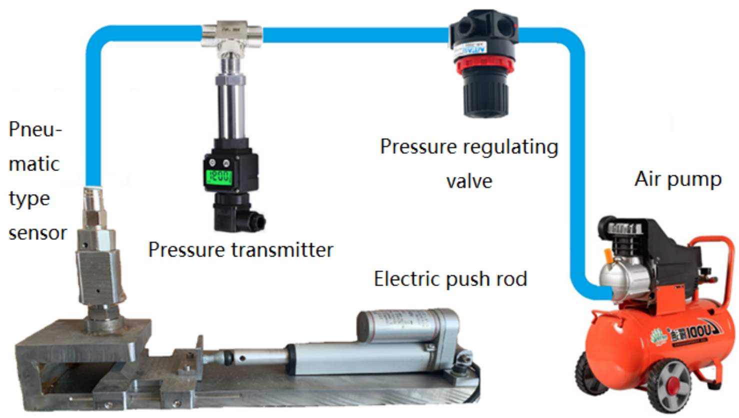

Fig. 1. Schematic design of overall air path of pneumatic sensor

3 Pneumatic sensor structure design

3.1 Principle of pneumatic sensor composition

The overall mechanical structure of the pneumatic sensor includes quick-plug base, quick-plug housing, one-way valve, linear slider and linear electric equipment, as shown in Figure 2. The linear electric device is installed on the test table, which can drive the linear slider to move back and forth. There is a trigger convex on the linear slider. When the linear slider runs to a specific position, the trigger valve stem of the pneumatic sensor can be triggered to lift the valve stem to a certain height. When the pneumatic sensor is not triggered, the one-way

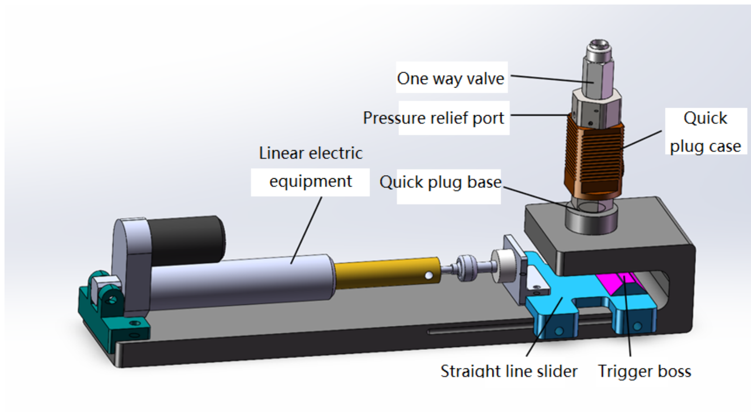

Fig. 2. Overall structure design of pneumatic sensor for equipment

valve is blocked, and the pipeline is isolated from the pressure relief port, so that there is no pressure drop. At this time, the spring performs unilateral restraint on the trigger valve stem, so that the trigger valve stem will not cause vibration and mistrigger the one-way valve. When the valve stem of the pneumatic sensor is triggered, the valve stem is triggered to move up a certain distance, and the cone valve core in the one-way valve is jacked up. The air path is connected with the pressure relief port, and the gas is removed from the pressure relief port, resulting in pressure drop. The roller can be optimized as a ball head structure.

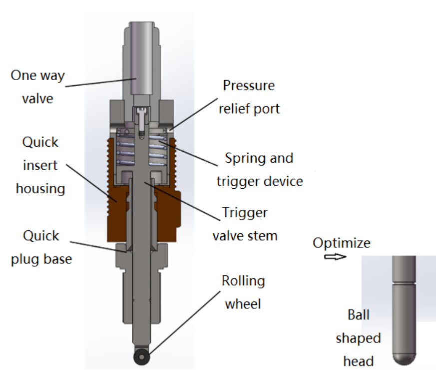

Fig. 3. Structural design of pneumatic sensor for equipment

3.2 Decomposition of inclined plane trigger force

When the linear slider is in contact with the valve stem, the force interaction between the valve stem and the inclined plane in front of the linear slider will be generated, and the valve stem will be lifted through the force transmission between the inclined planes. The force decomposition and analysis are carried out in this case, as shown in Figure 4. Where α is the Angle between the inclined

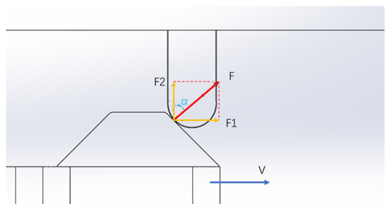

Fig. 4. Contact force decomposition diagram of linear slider

plane and the ground, F is the total force when the inclined plane contacts the valve stem, and F is decomposed into the horizontal and vertical directions F_1 and F_2.

$$\begin{aligned} F_1 = &\quad F \cdot \cos(\alpha) \\ F_2 = &\quad F \cdot \sin(\alpha) \end{aligned} \tag{1}$$

F_1 is the operating resistance of the pneumatic sensor to the straight-line moving structure, and F_2 is the force required to lift the valve stem. When the stem acceleration during lifting is not considered, the magnitude of F_2 is equal to the sum of stem gravity and spring resistance, i.e

$$F_2 = mg + k\Delta x \tag{2}$$

At the same time, the magnitude of the resistance F1 can be calculated

$$F_1 = F_2 \cdot \tan(\alpha) = (mg + k\delta x)\tan(\alpha) \tag{3}$$

The stem mass is 0.1kg, the beveling Angle α is 45 degrees, the lifting distance is 5mm, the spring stiffness is 0.75N/mm, and the precompression amount is 3mm, so F1=F2=7N and F=10N are calculated.

3.3 Stem force simulation analysis

The Simulation plug-in is used in solidworks to carry out finite element simulation analysis of the valve stem. The simulation parameters are shown in Table 1. The finite element simulation is carried out on the sensor stem for equipment and sensor stem for cylinder respectively. When 10N force is applied, the stress

Table 1. Simulation parameters of backforce distance

Fixed position	Direction of F	Material
Valve stem disc	Ball head bevel	304 steel

Poisson's ratio	Modulus of elasticity/GPa	Strength of tension/MPa	Strength of yield/MPa
0.29	190	1035	206

of valve stem is shown in Figure 8 and Figure 10. It can be seen that the maximum stress of the system is $8.13E + 06N/m^2$ and $1.43E + 07N/m^2$, while the yield force of 304 steel is $2.068e + 08N/m^2$, which is far from reaching the yield stress and the structure is safe. From the deformation results shown in Figure 5 and Figure 6, it can be seen that the maximum deformation is $0.0303mm$ and $0.0374mm$, and the overall shape variable is very small. As mentioned above, the

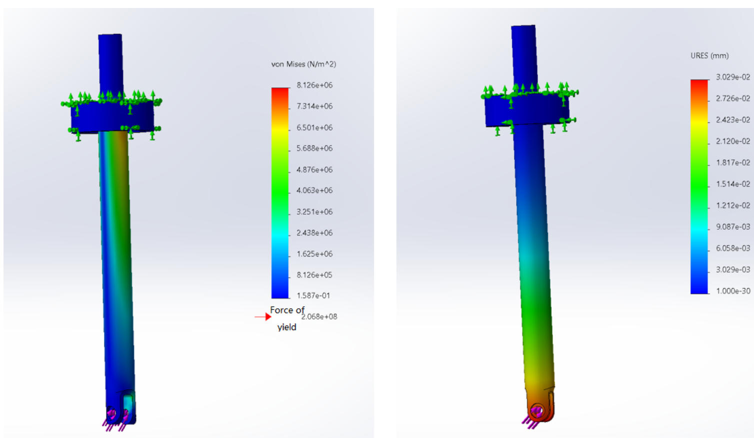

Fig. 5. Stress and deformation analysis of pneumatic sensor stem by finite element simulation

finite element simulation results are within the acceptable range, and the stress distribution is consistent with the theoretical and actual engineering phenomena. It is feasible to use the finite element method to analyze the force contact problem, and it can also provide some reference for practical operation.

3.4 Aerodynamic simulation of pneumatic sensor based on amesim

The model of the pneumatic part of the pneumatic sensor is built in AMESim as follows. The left air pressure source is set as the ideal air pressure source, and the output gas pressure after passing through the pressure reducing valve is $0.06MPa$. The adjustable throttle valve is used to simulate the one-way valve in the sensor, and the opening degree of the throttle valve is set to 0 to simulate the one-way valve when closed. Adjusting the opening of the throttle valve can simulate the triggering of the check valve by the pneumatic sensor. When the

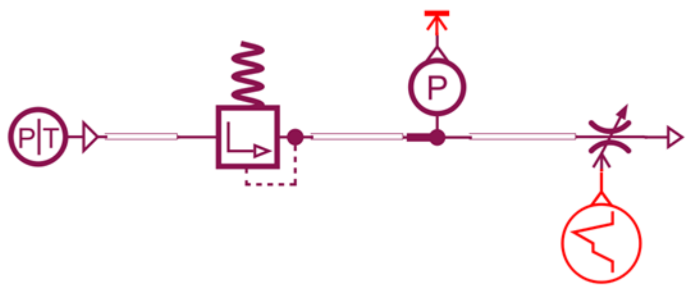

Fig. 6. Aerodynamic characteristic model of AMESim pneumatic sensor

starting sensor is triggered in the third second, the pressure drop can reach $0.02MPa$ in about 3.3 seconds, and the system pressure drops to about $0.01Mpa$ in the fourth second, which meets the technical requirements. The relationship between the length and diameter of the trachea between the pressure transmitter and the check valve on the change of pneumatic response time and pressure drop was explored. The calculation was carried out in AMESim. The length of the trachea was set as $2m$, $4m$ and $6m$ respectively, and the outer diameter of the trachea was $10mm$ and $12mm$ respectively. The more obvious the pressure reduction is, the less the impact on the aerodynamic characteristics is overall, and the pressure reduction can meet the applicable requirements. In addition, the relationship between pressure drop and flow before and after triggering can be seen from Figure 8.

3.5 Pneumatic sensor system test

After the completion of the whole system design and module debugging, the assembly and debugging of pneumatic sensors and the measurement of pressure change values are carried out. The assembly diagram of pneumatic sensor for equipment is shown in Figure 16, and the assembly diagram of pneumatic sensor for cylinder is shown in Figure 8:

Set up a test platform for air pressure change, which is composed of pneumatic sensor for equipment and silo test platform, test whether the air pressure change after trigger can reach the expected value, and record the trigger response time. The torque test platform is shown in Figure 9: Test instructions: pneumatic sensor equipment to meet the linear motion detection range:

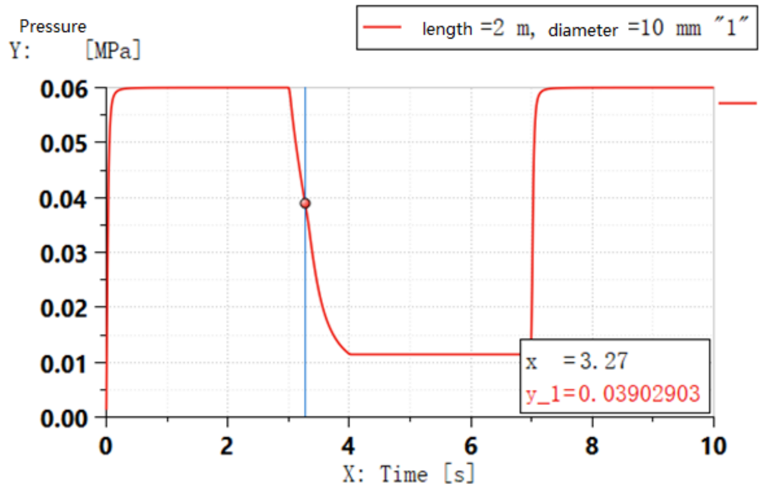

Fig. 7. Pneumatic sensor triggers pressure change

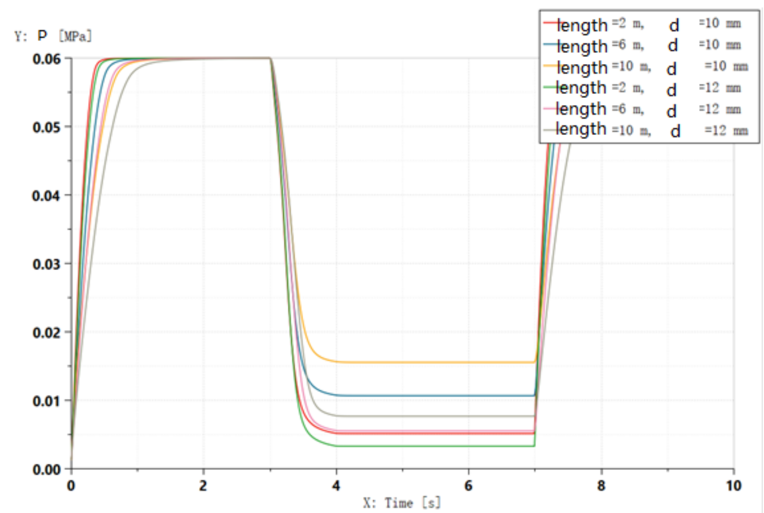

Fig. 8. Influence of air pipe on aerodynamic characteristics

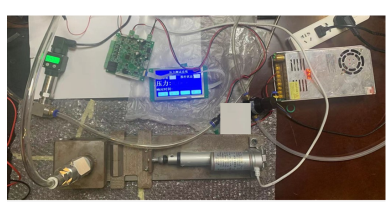

Fig. 9. Pneumatic sensor test bench for equipment

Table 2. Simulation parameters of backforce distance

num	Speed mm/s	Pre_trigger _pressure /MPa	Post_trigger _pressure /MPa	Drop_in_ pressure /MPa	Linear_trigger _resistance /N	Time_ response /s
01	20	0.06	0.01	0.05	3.6	0.55
02	20	0.06	0.02	0.04	3.4	0.52
03	20	0.06	0.02	0.04	3.6	0.58
04	20	0.06	0.01	0.05	3.2	0.51
05	30	0.06	0.01	0.05	3.4	0.53
06	30	0.06	0.02	0.04	3.3	0.52
07	30	0.06	0.02	0.04	3.6	0.58
08	30	0.06	0.02	0.04	3.4	0.51
09	50	0.06	0.01	0.05	3.2	0.53
10	50	0.06	0.01	0.05	3.2	0.58
11	50	0.06	0.02	0.04	3.4	0.51
12	50	0.06	0.01	0.05	3.5	0.53
13	60	0.06	0.02	0.04	3.5	0.52
14	60	0.06	0.01	0.05	3.5	0.58
15	60	0.06	0.02	0.04	3.5	0.50
16	60	0.06	0.02	0.04	3.4	0.49

$20mm/s - 60mm/s$; According to the inclined plane 45° speed is decomposed into horizontal and vertical equal relative speed, and the rotation radius of the rotating motion is greater than 1m, the position detection can be regarded as the relative position detection of the axis direction of the pneumatic sensor, $v = 3 * 3.14 * 1000/180 = 50mm/s$, so it also meets the detection range of the rotating motion of $1°/s - 3°/s$; The comprehensive response time of equipment positioning with pneumatic sensor is less than 1s, and the comprehensive response time of cylinder positioning with pneumatic sensor is also less than 1s. According to the response time, the requirements of linear motion positioning accuracy $2mm$ and rotary motion positioning accuracy $+1°$ can be achieved by the control technology. The internal closing pressure of the pneumatic sensor is $0.06MPa$, the trigger internal pressure drop is greater than $0.02MPa$, and the working pressure of the cylinder is $0.5MPa$.

4 Conclusion

Through the simulation analysis of the pneumatic sensor in nuclear power plant, a highly reliable pneumatic sensor is designed and developed, which provides a new idea for the realization of the robot's rapid autonomous disassembly and assembly of the sensor under the radiation environment, which is convenient for the maintenance and repair of the sensor, and reduces the maintenance cost.

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