Design of A Free Floating Ultrasonic Inner Spherical Detector for Pressure Pipeline

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Abstract. Ultrasonic inspection of the corrosion and scaling in industrial pressure pipelines is necessary due to the adverse effects of defects on medium flow and heat transfer. In this paper, a free floating ultrasonic inner spherical detector has been designed to detect and locate defects in pipelines. The flange mechanical structure of ultrasonic inner detection intelligent ball meets the internal space requirements and external environmental requirements. They are connected of two parts flange type. A complete set of spherical shell structure design covering the functions of sealing and external pressure resistance is proposed and completed. One part is the inner sphere, and the other is the outer shell. Pipeline experiments show that the spherical detector can reach the exit smoothly through curved pipes, inclined pipes and vertical pipes without jamming and stable motion attitude, collects all kinds of information along the way, determines the existence of defects and achieves accurate positioning.

1. Introduction

A large number of researches have been carried out on the detection technology of pressure pipelines at home and abroad. The research on the detection of pipelines has been carried out earlier in foreign countries. In the second half of the last century, the United States, Japan, Germany, Canada and other countries have started the detection of pipelines. The development of the device, after decades of continuous research, has also formed a lot of results [1-3]. At present, the main pipeline detection technologies include magnetic flux leakage detection, ultrasonic detection, eddy current detection, and detection based on optical principles. Among them, the most widely used magnetic flux leakage detection method and ultrasonic detection method have been successfully developed corresponding pipeline detectors [4].

Tianjin University has proposed a spherical device for pipeline detection. For example, Cui Yaoyao of Tianda University [5-7] proposed a spherical inner detector structure design for the detection of submarine pipelines for small leaks, that is, the flange-type sealed spherical shell is filled with water. Hearing device, inertial navigation module and magnetic sensor, circuit board, power supply module, etc. The smart ball flows with the liquid in the tube, and collects information about the leakage sound in the tube, its own motion information, and the magnetic field information in the tube along the way.

In the process of pressure pipeline inspection, the primary problem is to avoid pipe jams. Therefore, it is feasible to use small-volume spherical or cylindrical in-pipe detectors. However, for complex industrial pipelines, it contains 180-degree sharp bends, etc. Structure, so the passing capacity of the
spherical inner detector will be better than that of the cylindrical inner detector. Ultrasonic testing can well meet the detection requirements for potential safety hazards such as serious corrosion and blockage of pipelines.

2. Detection System Design

2.1. Principle of Ultrasonic Internal Testing

The core of the development of the floating ball for ultrasonic internal inspection of pressure pipelines is to reasonably assemble the spherical shell, densely packed ultrasonic probe, ultrasonic card, accelerometer, magnetometer, battery, embedded computing platform, memory and other components in a narrow spherical space, and form an integrated space. Set of ultrasonic signal receiving and sending control, synchronization, processing and other functions. The entire free-floating smart ball device includes spherical metal inner shell, ultrasonic focusing thickness measurement probe, multi-channel ultrasonic card, silicone shell, accelerometer, magnetometer, high-efficiency battery, embedded system, storage, threaded plug and other components.

In order to adapt to different pipelines, different sizes of spherical shells can be fixed outside the core spherical shell of the detector. This structure improves the interchangeability of the inner detector and avoids designing and manufacturing different core spherical shells for different sizes of pipelines, with different designs. Trouble with the size of the circuit board. A large number of ultrasonic thickness measuring probes are evenly and densely distributed on the surface of the steel spherical shell. The assembly diagram between the probe, the spherical inner shell and the silica gel shell is shown in Figure 1.

![Figure 1. Schematic diagram of the assembly between the probe, the spherical inner shell and the silicone shell.](image)

The probe adopts a circular wafer, the wafers are distributed along a spherical surface, and the focusing adopts an acoustic lens method, and a concave lens made of an acoustic lens material with a higher sound velocity than water is used to focus on a specific position through a curvature design. When the inner spherical detector is drifting, there is always a set of probe sound beams perpendicular or substantially perpendicular to the inner wall along the pipe circumference, so that the probe can receive ultrasonic signals to detect the corrosion of the pipe wall. Ultrasonic signals are processed by a multi-channel, highly integrated, low-power ultrasonic card. All thickness measurement functions such as ultrasonic transmission control, receiving control, high-speed A/D acquisition, and digital processing can be completed by the ultrasonic signal acquisition card alone. And stored in the storage of the instrument device.

The inner spherical detector also includes accelerometer, magnetometer and high-efficiency battery. Through the acceleration information recorded by the built-in three-axis accelerometer, the distance traveled by the spherical detector floating in the pipeline can be obtained. The corrosion data collected by the ultrasonic probe, combined with the distance and position information calculated by the accelerometer data, can locate the corrosion point of the pipeline. The magnetometer can detect the approximate position of the ball thickness measurement device from the outside of the pipeline with a magnetic sensitive element. The high-efficiency battery realizes long-distance power supply for multi-channel ultrasonic cards, accelerometers, and embedded systems, and its power should be able to
support the power required for the normal operation of the pipeline in the detection computing device over a long distance.

After the smart ball detection is completed, the finishing work is carried out through the ball receiving device. After the memory in the ball is taken out, the data is transferred to the PC and analyzed by the special software of the PC. Through the offline detection data analysis system to process the stored data, the corrosion of the entire pressure pipeline can be detected, thereby judging the safety status of the entire pressure pipeline system.

2.2. Mechanical structure of the inner detector housing
The inner spherical detector includes an internal aluminum pressure-bearing core ball shell, an internal collection and storage module, a motion sensor, and an external silicone elastic shell. With this structure, the pressure-bearing core remains basically unchanged for different pipe diameters, and only the size of the external support spherical shell needs to be changed, which reduces the cost of research and development.

The core spherical shell structure adopts the traditional flange type and O-ring sealing method. Compared with the radially sealed spherical shell, the flange type has advantages in terms of sealing performance, repeated disassembly without damage, and ease of installation. Ensure the pressure resistance of 1MPa; the external silicone shell adopts mold forming technology, which has the functions of shock absorption, wear resistance, and reduction of collision and friction noise. Different specifications of buoyancy materials can be loaded between the inner and outer spherical shells to adjust the buoyancy of the test ball in the pipeline; at the same time, the overall center of gravity is adjusted to make it as close to the center of the ball as possible, so that the test ball maintains the best motion posture.

The steel spherical shell is installed and structurally sealed, threads are machined on the edge of the hemispherical shell, and the spherical shell is connected and sealed through the threads and the sealing ring. One of the hemispherical shells has a through hole, which is sealed with a plug and a sealing ring. The plug corresponds to the position of the storage. When the test is completed, it is not necessary to open the entire steel spherical shell, just open the plug and take out the storage with special facilities. Just perform data analysis.

2.3. Study on diameter selection
The selection of the ratio of the diameter of the spherical detector to the diameter of the pipe plays a key role. If the ratio of the diameter of the spherical detector to the pipe diameter is too small, it will cause the spherical detector to enter other branches by mistake when it passes through the branch pipe during the floating process; if the diameter of the spherical detector is the same as the pipe diameter, the ratio is too large, it will cause the butterfly valve to be unable to pass through the pipeline, or the danger of jamming when passing through a turn.

Therefore, in the design process, the structure and size of the spherical detector are key design factors. The design of the internal structure is closely related to the convenience of the use process. In the assembly part of the spherical detector, the ball weight is emphasized. The ratio of gravity to buoyancy of the sphere should meet the requirements of drifting. By adjusting the weight in the ball, the position of the sphere in the fluid is determined. The gravity is greater than the buoyancy, and the spherical detector sinks at the bottom of the pipeline to float. When the buoyancy of the sphere is greater than the gravity, the spherical detector floats on the liquid.

When the internal spherical detector is used in the pipeline, the size of the spherical detector is not arbitrary determined by its structural environment and fluid environment and other comprehensive factors, which is restricted by the following factors.

2.3.1. Detect the influence of external factors on the sphere in the fluid
When the spherical detector floats with the fluid in the pipeline, the thrust of the sphere itself is affected by the fluid viscosity coefficient, the flow velocity, and the ratio of the diameter of the sphere to the
diameter of the pipeline. In this paper, Bernoulli equation is used to describe the pressure in the pipeline fluid of the test ball, and the best test ball diameter is determined by comparing the thrust force received under different diameter ratios between the pipeline and the test ball. The general form of Bernoulli equation is

\[ p_1 + \frac{1}{2} \rho v_1^2 + \rho gh_1 = p_2 + \frac{1}{2} \rho v_2^2 + \rho gh_2 \]  (1)

\[ p + \rho gh + \frac{1}{2} \rho v^2 = \text{constant} \]  (2)

\( \frac{1}{2} \rho v^2 \) is the part related to the flow velocity, which is the dynamic pressure, and \( p \) and \( \rho gh \) are the static pressure. The equation describes the energy conservation of the spherical detector in the fluid.

Since the detection spheres of different diameters occupy different proportions in the cross-section of the pipeline, the fluid passes through the gaps differently. According to the equation, the pressure will be lower where the flow velocity is high, and the pressure will change where the flow velocity is small. High, so the diameter of the sphere is not as big as possible.

In actual conditions, under the action of a stable flow state and gravity field, the applicable equation for an incompressible ideal fluid in a pipeline is

\[ p + \rho gh + \frac{1}{2} \rho v^2 = \text{constant} \]  (3)

The applicable environment is slowly changing flow, which means that in the fluid pipeline, the divergence angle of the direction of the fluid is small, the direction tends to be parallel, and the overall radius of curvature of the pipeline is large.

2.3.2. Internal Space Requirements of the Detector

The detector is equipped with a data acquisition platform, sensor modules including accelerometer and magnetometer modules, data transmission interfaces and batteries. Among them, in addition to the largest ultrasonic circuit board size that needs to be considered, the volume of the battery occupies most of the space inside the spherical detector. Due to the long running time of the detector, the length of the pipeline is hundreds of kilometers, and the fluid velocity is generally about 2m/s, the battery needs to be continuously powered for more than ten hours at least to meet the needs of detecting the entire pipeline. Choose a large-capacity battery of 3800mAH, and this type of large-capacity lithium battery has a larger volume and is also the larger part of the circuit structure. Therefore, when designing the size of the test ball, the inner diameter should be based on the ultrasonic circuit board, battery size, etc., and the minimum standard for smoothly accommodating the ultrasonic circuit board and battery.

2.3.3. Influencing Factors of Detector Wall Thickness

The wall thickness of the spherical detector is also an important factor. If the wall thickness is too large, the available internal space under the same outer diameter will become smaller, making the assembly of internal components difficult, and at the same time increasing the weight of the spherical detector. If the wall thickness is too small, the pressure-bearing capacity of the detector will decrease, and it will be easily damaged under high pressure. Through the stress analysis of the spherical shell, it is known that a wall thickness of at least 4mm is required to withstand a pressure of 1Mpa. Since the spherical detector may continuously collide with the inner wall in the pipeline, the ball needs to have a certain degree of impact resistance. For safety, the thickness of the spherical detector is 5mm for higher reliability.

3. Test

The actual working performance of the intelligent ball is tested after the ultrasonic internal testing device of the drifting ball is assembled and the pipeline test environment is available. Figure 2 shows the spherical detector in the process of testing and debugging.
Figure 2. The spherical detector in the detection and debugging

The ultrasonic internal inspection technology of pressure pipeline takes the industrial pipe as the testing object, and a typical industrial pipe is selected in the study, whose nominal diameter is DN350, outer diameter 377mm and thickness 10mm. Working pressure is greater than 0.1 MPA, usually from 0.5MPa to 1MPa. The built pipeline system simulates the various trends of the actual pipeline arrangement, including the downward trend, the rising trend and the horizontal trend of the pipeline. In addition, there are 180-degree bends and 90-degree bends, which can simulate the various trends of the pipeline detection device in detecting the actual pipeline, so as to find all kinds of problems that may be encountered in the actual inspection in advance. The device also includes a loop composed of a water tank, a water pump and a pipe, which is used to simulate the medium flow. The speed of the detection device in the simulated pipeline is controlled by controlling the speed of the water flow, and the best speed is found to detect the actual pipeline. The simulated corrosion defects of 4mm diameter and depth 2mm are distributed inside the sample pipe to simulate the corrosion of the actual pipeline in application. A sealing ring link is used between the pipe and the pipe to simulate the welds in the actual pipeline, and other defects are included in the pipe to simulate all kinds of defects that may occur in the actual pipeline. Figure 3 shows the test pipeline system of pipe diameter 350mm.

Figure 3 Test piping system with a pipe diameter of 350mm

In the test, the test pipeline is filled with liquid, and the pig is first used for pigging operation and the pigging effect is checked; after completion, the test ball is sent into the test pipeline for ultrasonic internal inspection.

After the entire sphere detection process is completed, the finishing work is carried out through the ball receiving device, and the memory in the detection sphere is taken out, and the data is transferred to the PC, and the PC special software is used for analysis. In the specific processing, the ultrasonic thickness measurement signal obtained by the array probe is displayed in color to obtain the wall thickness corrosion and thinning of the pressure pipeline, so as to judge the safety status of the entire pressure pipeline system.

4. Conclusion
The test results show that the test ball can smoothly pass through the pipeline test platform built. Offline data analysis, obtain the data of the existing signal somewhere in the straight pipe section, perform echo
processing and calculation, and obtain the thickness data. The wall thickness at the position of the straight pipe section of the pipeline is 7.9mm. For a pipeline with a design thickness of 8.0mm and a thickness gauge of 8.1mm measured by the thickness gauge, the test results can meet the engineering inspection requirements. During the test, there was no good signal and data in the detection of the elbow, which may be due to the fact that the number of probes is not enough, and the water path at the elbow changes greatly.

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