Deformation and stress analysis of cup on pipeline inspection gauge based on reverse measurement

Zhong Chen | Xiaoyang Qiu | Lingling Yang

Abstract
The pipeline inspection gauge (PIG) is one of the most significant gauges in the field of oil–gas storage and transportation. It is essential to use PIG to clean and detect petroleum and natural gas pipelines. Predicting the deformation and stress distribution of the cup on the PIG is essential before pigging. To enhance these predictions, especially the deformation of the cup, a method for measuring the deformation of the cup based on reverse measurement was introduced and a novel finite element (FE) simulation model for investigation of the deformation of cups was proposed and verified in this paper. The point cloud data of the cup before and after entering the pipe can be obtained by the three-dimensional (3D) laser scanner. Comparing the obtained point cloud data can measure the deformation of the cup. In addition, a 3D FE model was created to predict the deformation of the cup and the effective stress on the contact area. The result shows that there is a linear relationship between circumferential deformation and interference, while there is a nonlinear relationship between axial deformation, effective stress, and interference. These results provide a better understanding of the complex behavior of PIG during pigging.

Keywords
energy systems, natural gas, petroleum, planning, pipeline inspection gauge

1 | INTRODUCTION
Energy is the driving force of economic development. Energy substances represented by petroleum and natural gas not only affect the world political pattern but are also related to world peace and tranquility. In recent years, the demand for natural gas, as a kind of clean energy, is increasing. Pipeline transport, as one of the five most important transport manners, is the most economic and efficient transport manner for natural gas and petroleum.1 However, long usage for transporting natural gas or petroleum will block the pipe and reduce the effective transportation area, which will bring a high risk for the leakage of natural gas and petroleum. So, it is very necessary to clean and inspect pipelines regularly. The pigging operation is a common practice in the petroleum and gas industry.2,3 The pipeline inspection gauge, often called “PIG,” is always applied to inspect and clean the pipeline.4

The basic design of a PIG consists of a rigid body, cups, and optional components such as odometer wheels, sensors, and so on.5 No matter the traditional PIG is only...
used for cleaning pipes or the intelligent PIG can be used to inspect the pipe, the power of PIG comes from the differential pressure of the fluid during the pigging operation.\(^6\) The cups which are tightly close to the inner wall of the pipe can perform the tasks such as sealing and cleaning.\(^7\) The frictional contact between cups and the inner wall determines the pigging ability.\(^8\) Numerous experts have conducted a great deal of research on the frictional contact behavior between the cups and pipe. However, the stress distribution of the cup is complex and the measurement and calculation of contact stress have always been a complicated problem. Due to the nonaccessibility of the contact interface, it is difficult to obtain the internal information of the contact interface using conventional measurement technology.\(^9\) To measure the contact stress, some scholars have proposed some novel methods, such as utilizing a thin film sensor,\(^10\) three-dimensional (3D) digital image correlation,\(^11\) photo elastic measurement method,\(^12\) and so on. However, the methods mentioned above are not applicable in a dark environment like the inner pipe. The real-time measurement of contact stress between cups and pipes is still a challenging task at present. The most commonly used method is still utilizing finite element (FE) software to simulate, such as ANSYS, ABAQUS, and MSC software. To verify the rationality of the FE simulation results, direct or indirect experiments will be often carried out. Zhang et al.\(^13\) and Liu et al.\(^14\) all designed a traction experiment. Pulled by a step-less speed electromagnetism winch, the PIG can run in the pipe at a uniform speed and the tension sensor will record the value of traction force. By comparing the value of tractive force obtained by traction experiment and the value of frictional force obtained by simulation to verify the rationality of the simulation results. Zhang et al.\(^15\) studied the friction and dynamic characteristics of PIG’s sealing disc passing through girth weld and divided the process of passing through girth weld into three stages. Liu et al.\(^14\) established a 3D FE model to study the traveling ability of PIG when running in the elbow under different friction coefficients and introduced the concept of traveling ability to describe blockage avoidance. The concept can be defined by sealing performance, driving performance, and collision possibility. Zhang et al.\(^15\) studied the stress and strain on the outer edge of the cup in a dented pipe and concluded that the thickness of the cup has the greatest impact on the stress and strain distribution. Cao et al.\(^16\) combine theoretical analysis and numerical simulation to analyze the compressive stress on the contact area when the PIG runs in straight pipe, elbow, and anomaly. The relationship between the radial stress and position was obtained. Hendrix et al.\(^17\) designed a static and dynamic experimental setup to investigate the frictional behavior of the sealing disc. The setup can be used to systematically study the effect of various parameters including the oversize, force ratio, thickness, and E-modulus.

The fit between the cup and pipe belongs to interference. There is no doubt that the cup will deform after entering. The deformation of the cup directly affects the pigging effect and antiblocking ability. However, the restriction of pipe makes the deformation difficult to measure. Some experts have studied the deformation of the sealing disc because the deformation of the sealing disc is larger and the structure is simple. O’Donoghue\(^18\) presents a simplified model which assumes that the deformed sealing disc adopts the shape of a circular arc. But the model does not give the specific deformation. Zhu et al.\(^19\) proposed a 2D axisymmetric nonlinear FE model to study the impacts of interference, thickness, chamfer dimension, and clamping rate on the deflection angle. Wang\(^20\) pressed the PIG into the acrylic pipe and measure the axial deformation of the sealing disc with a high-speed camera. But this method is only applicable to the PIG with a small size. Once the diameter of the sealing disc is large, the cup is easy to break the acrylic pipe.

According to the previous studies, numerous experts have used FE simulation to study the contact behavior between the cup and pipe wall. Pipe types includes straight pipe, dented pipe, elbow pipe, and so on. However, recent research shows that few researchers have paid attention to the deformation of the cup and there is no effective method to measure the deformation of the cup. Hence, it is meaningful and necessary to propose a method for measuring axial deformation. In this paper, the deformation of the cup can be obtained by the comparison of the point cloud data using Geomagic software. Based on the FE model, the relationship between the deformation of the cup and effective stress on the contact area with various interference was obtained.

2 | EXPERIMENTAL STUDY

2.1 | Experimental device

The PIG (Chengde Katop Equipment Manufacturing Co. Ltd) used in this paper is shown in Figure 1. The cup must be inserted into the pipe, then the deformation of the cup can be studied. According to the research of Zhu et al.\(^21\) the PIG gravity almost has no effect on the frictional force of a PIG. So, gravity also has no effect on the deformation of the cup caused by frictional force. Hence, the electronic universal testing machine
(Changchun Research Institute of Test Machine Co.), as shown in Figure 2A was used to press the cup into the pipe. The pipe was fixed on the workbench of the machine and the cup fixed by two spacers was set in the center of the inlet of the pipe. During the experiment, the cup is easy to deflect when the push rod presses the cup into the pipe, due to the misalignment of the cup. So, chamfering is set at the inlet of the pipe and a leveling gauge, as shown in Figure 2B, was set on the surface of the spacer to judge whether the cup is placed horizontally. The push rod can press the cup into the pipe at a low speed. The deformation of the cup can be considered stable in the ideal state because of interference fit. The deformation of the cup can be measured as long as the cup completely enters the pipe. Therefore, one section of steel pipe was used to replace the pipe. To analyze the deformation during the contact between the cup and inner wall under different interference, four different inner diameter steel pipes (208, 206, 204, and 202 mm) were manufactured in this experiment. The cup interference can be calculated by Equation (1). The interference values are 1.15%, 2.14%, 3.14%, and 4.16%, respectively.

\[
\delta = \frac{D_{\text{cup}} - D_{\text{pipe}}}{D_{\text{pipe}}} \times 100\%,
\]

where \(\delta\) is the interference value, \(D_{\text{cup}}\) is the outer diameter of the original cup (see Section 3.1) and \(D_{\text{pipe}}\) is the inner diameter of the pipe.

To obtain the surface shape of the cup after entering the pipe, the FARO platinum 10 ft laser scan arm (Faro Co., Ltd), hereinafter referred to as scanner in this paper, as shown in Figure 2C, was used to obtain the point cloud data of the surface of the cup. The measurement range of the scanner is 3.0 m in the radial direction, the ball test accuracy is ±0.046 mm, the cone test accuracy is ±0.052 mm, the laser scanning distance is 89–184 mm, and the scanning accuracy is 0.05 mm. By scanning the measured object through the scanner, it can obtain spatial coordinates and surface information of the object based on the laser triangulation measurement principle. The laser scan arm used a group of sensors in its arm for exacting the coordinate of the probe’s position in space. A laser ray will be emitted from the probe and will project on the surface of the measured object. Laser ray projection distance in space will automatically be recounted in dependence on the angle and distance of the probe. This reverse measurement can determine a position of several thousand points in seconds and

**FIGURE 1** The pipeline inspection gauge used in this paper.

**FIGURE 2** (A) Electronic universal testing machine, (B) press the cup into the pipe, and (C) FARO platinum 10 ft laser scan arm.
generate point cloud data of the scanned object. Therefore, the deformation of the cup can be measured through this reverse measurement.

### 2.2 Measurement of deformation of the cup

The cup enters the pipe whose inner diameter is less than the diameter of the cup. There is no doubt that the soft cup will be squeezed circumferentially by the external force of the pipe wall. The external force of the pipe wall is distributed along the circumference, leading to the circumferential deformation of the cup. In addition, as the cup contacts the pipe wall, friction force will be formed between the cup and pipe wall. And the friction force is oriented parallel to the direction of the movement of the cup. Under the combined action of the external force of the pipe wall \((F_{wall})\) and friction force \((F_{fric})\), as shown in Figure 3, the resultant force \((F_{res})\) will make the cup deform in both the axial direction and circumferential deformation, and the edge of the cup will converge towards the center of the cup. This phenomenon is reflected in the fact that the edge of the cup does not fit with the pipe wall. It can be seen in Figure 4, \(\Delta x\) is the circumferential deformation and \(\Delta z\) is the axial deformation. It is not difficult to obtain the circumferential deformation if the edge of the cup is close tightly to the inner wall of the pipe. However, the separation between the edge of the cup and the inner wall of the pipe makes it difficult to measure the circumferential deformation of the cup. In this paper, the shape of the back surface of the cup after it enters the pipe can be obtained inversely by the scanner. The contact force between the cup and the pipe wall is large, and the pipe wall can fix the cup. So, it can be regarded that the deformation of the cup changes little in the ideal pipe when the cup enters the pipe completely. So, to scan and extract the surface successfully, it just needs to press the cup into the pipe completely.

When the cup completely enters the pipe, the scanner was used to obtain the point cloud of the back surface of the deformed cup. Before processing and measuring, the point cloud was transformed into a triangular mesh model by connecting various points. After patched by Geomagic software, the boundary of the triangular mesh model can be fitted by a circle. The diameter of fitted the circle can be regarded as the diameter of the edge of the deformed cup. So, the circumferential deformation \((\Delta x)\) can be calculated by means of Equation (2). The point cloud data of the cup which enters pipes with different inner diameters were shown in Figure 5. It can be seen from Figure 5A–D, that the blue area is the shape of the cup, and the red line is the edge of the fitting circle. After fitting the boundary, the diameter of the fitting circle was obtained and circumferential deformation can be seen in Table 1.

\[
\Delta x = \frac{D - D_{fit}}{2},
\]

where \(\Delta x\) presents the circumferential deformation of the cup; \(D\) presents the outer diameter of the undeformed original cup; \(D_{fit}\) presents the outer diameter of the fit circle.

The axial deformation of the cup is quite small, and it is more difficult to measure than circumferential deformation due to the resistance of the pipe. However, the point cloud data of the cup before and after entering the pipe can be also obtained by the scanner, as shown in Figure 6. After obtaining the triangular mesh model of the cup and deformed cup, if the two models were aligned based on the spacer, the distance between the edge of the cup is the axial deformation of the cup. Therefore, Geomagic Control X software was used to obtain the deviation between the two models. Geomagic Control X software is a professional quality control and dimension inspection software, which has the function of 3D error detection. The deviation at the cup edge can be regarded as the distance between the cup edge.
FIGURE 5 The point cloud data of the cup after the cup enters the pipe with various interference $\delta$: (A) $\delta = 1.15\%$, (B) $\delta = 2.14\%$, (C) $\delta = 3.14\%$, and (D) $\delta = 4.16\%$.

TABLE 1 The circumferential deformation of the cup with interference of 1.15%, 2.14%, 3.14%, and 4.16%.

| Interference (%) | Diameter of cup (mm) | Diameter of fitting circle (mm) | Circumferential deformation (mm) |
|------------------|----------------------|---------------------------------|---------------------------------|
| 1.15             | 210.4                | 206.0297                        | 2.18515                         |
| 2.14             | 210.4                | 202.1580                        | 4.121                           |
| 3.14             | 210.4                | 200.5093                        | 4.94535                         |
| 4.16             | 210.4                | 197.9988                        | 6.2006                           |

In this paper, the triangular mesh models of the cup before entering the cup were set as reference data, and the triangular mesh models of the cup after entering the pipe were set as test data. After importing the data, the two groups of data were applied to the initial alignment, and then applied to the best fit alignment. Six corners of the hex head bolt which was used to fix the cup can just be used as reference points during alignment operation.
as can be seen in Figure 7. The green area is the reference data, while the blue area is the test data. Combining Figures 4 and 8, the deviation between the two surfaces can be regarded as the axial deformation of the cup. The measurement principle of axial deformation of the cup is shown in Figure 9.

The cup was cut in ZX plane and ZY plane, respectively for 2D comparison and four points (A, B, C, and D), as shown in Figure 8, on the edge of the cup were selected to measure the axial deformation to compare the data more intuitively. Figure 10A–D shows the comparing results of the axial deformation with various interference. The black edge in the figure is the edge of the reference data section, while the other edge is the edge of the test data. The deviation (Dev.) can be regarded as the axial deformation of the cup.

There are errors, such as cup misalignment, scanner error, point cloud processing error, and so on in the experiment. So, the averages of the deviation at the four points (Dev. (A), Dev. (B), Dev. (C), Dev. (D)) were computed, as shown in Figure 8, and the average value can be regarded as main axial deformation ($\Delta z_{1}$), which can be calculated by means of Equation (3). In an ideal condition, the deviation between reference data and test data in the part of “spacer” ($O_{i}$) approximately equals to 0. However, the push rod cannot be accurately aligned during the process of pressing the cup into the cup and the surface of the cup is not an accurate circle, the cup does not enter the pipe vertically. It brings deviations in the process of data alignment. In addition, the PIG can hardly be completely aligned under real working conditions. Therefore, compared with the original state, the spacer and cup will be inclined slightly after entering the pipe. But it should be noticed that the deviation of the spacers is very small and the deviation in the part of the spacer are all negative deviations. It indicates that during the operation of best fit alignment, the deviation direction in the part of the spacer is opposite to the direction of axial deformation. So, for the overall axial deformation, the average negative deviation at the surface of the spacer ($\Delta z_{2}$), which can be calculated by means of Equation (4), should be supplemented. At
the cross-section and vertical section spacers, take three points equidistant from the center of the circle to the outside, and the average value of the deviation at six points in two directions is taken as the deviation at the spacer (see Table 2). So, the axial deformation of the cup \((\Delta_z)\) can be calculated by Equation (5). After calculating, the axial deformation of the cup with the interference of 1.15%, 2.14%, 3.14%, and 4.16%. is shown in Table 2.

\[
\Delta_{z1} = \frac{\text{Dev. (A)} + \text{Dev. (B)} + \text{Dev. (C)} + \text{Dev. (D)}}{4},
\]

\[
\Delta_{z2} = \text{Dev. (O)},
\]

\[
\Delta_z = \Delta_{z1} + \Delta_{z2}
= \frac{\text{Dev. (A)} + \text{Dev. (B)} + \text{Dev. (C)} + \text{Dev. (D)}}{4} + |\text{Dev. (O)}|.
\]

\[3 \mid \text{FE ANALYSIS OF CUP DEFORMATION}\]

\[3.1 \mid \text{3D FE model of the cup}\]

The friction contact between PIG and pipe is a highly nonlinear contact-impact problem. It involves geometric nonlinearity, material nonlinear, and contact nonlinear.
If a traditional implicit dynamics algorithm is used to solve this kind of highly nonlinear problem, the calculation results are difficult to converge and the amount of calculation is very large. So, the explicit dynamic algorithm was adopted in this paper. The whole simulation process and software we used are as followed: Workbench 19.2 for preprocessing, ANSYS LSDYNA for solving, and LS-prepost for postprocessing.

The solid model of the cup must be established correctly before the FE analysis. However, the shape of the cup, as shown in Figure 11A, deviates from the design size and the curve of the cup is irregular. In addition, the cup is made from polyurethane and has the characteristic of elasticity. In the process of measuring with a vernier caliper, the measuring claw needs to clamp the cup and will squeeze the cup, which will make the diameter of the cup smaller. To obtain an accurate model of the cup, the idea of reverse design was utilized in this paper. The scanner was used to obtain the 3D point cloud of the cup. The surface of the cup was sprayed with the developer before scanning and the point data was patched using Geomagic software after scanning to obtain the relatively perfect point cloud data. The point cloud data of the cup is shown in Figure 11B. After measuring the point cloud data, the actual outer diameter of the cup is 210.4 mm, which is different from the design data given by the manufacturer (211 mm). The model of the cup needs to be analyzed by the FE method, so the point cloud data need to be converted to a solid model and carry out a simplified treatment. After rounding the boundary and bolt holes, the solid model, as shown in Figure 11C, was set using Geomagic software. The size and partial section of the cup can be seen in Figure 12.

The parameters of the pipe, mandrel, and spacer are listed in Table 3. The material of the mandrel and spacer is Q235 steel which is typically used in service conditions. The cup is made of polyurethane rubber. Existing studies have measured the axial deformation of the cup with various interference (Table 2). The deformation Δz1 and Δz2 of the cup are calculated based on these measurements.

![Figure 11: The model of the cup.](image)

(A) Physical model, (B) the point cloud data, and (C) the solid model.

![Figure 12: Section of the cup](image)

Table 2: The axial deformation of the cup with various interference

| Deviation (mm) | Interference (%) | 1.15 | 2.14 | 3.14 | 4.16 |
|---------------|------------------|-----|-----|-----|-----|
| A             |                  | 0.4655 | 1.2792 | 2.0067 | 6.2982 |
| B             |                  | 1.5928 | 2.2104 | 2.1071 | 4.6737 |
| C             |                  | 0.6228 | 1.3256 | 2.4116 | 4.2722 |
| D             |                  | 0.9416 | 1.5711 | 2.5977 | 6.0908 |
| Deformation Δz1 |                | 0.905675 | 1.596575 | 2.280775 | 5.333725 |
| O₁          |                | -0.5816 | -0.7891 | -1.3375 | -0.2003 |
| O₂          |                | -0.3439 | -0.9203 | -1.3929 | -0.0437 |
| O₃          |                | -0.5276 | -0.6576 | -1.2214 | -0.3059 |
| O₄          |                | -0.5883 | -0.9342 | -1.4576 | -0.2810 |
| O₅          |                | -0.5923 | -0.7924 | -1.3398 | -0.1951 |
| O₆          |                | -0.5049 | -0.6725 | -1.2411 | -0.1942 |
| Deformation Δz2 |            | -0.5231 | -0.7935 | -1.3317 | -0.2034 |
| Deformation Δz |              | 1.4288 | 2.3901 | 3.6125 | 5.5371 |

Table 3: The parameters of pipe and PIG

| Names                  | Values                  |
|------------------------|-------------------------|
| Pipe internal diameter D | 208 mm/206 mm/204 mm/202 mm |
| Pipe wall thickness     | 10 mm                   |
| Spacer diameter         | 140 mm                  |
| Spacer thickness        | 10 mm                   |
| Mandrel diameter        | 70 mm                   |
| Young's modulus         | 2.01 × 10⁵ MPa          |
| Poisson’s ratio         | 0.3                     |
proved that two-parameter Mooney–Rivlin model can better describe the nonlinear stress–strain behavior of rubber materials in numerical simulation. So, utilizing the Mooney–Rivlin model to define the material of the cup is reasonable. The two-parameter Mooney–Rivlin model can be described by Equation (6). The hardness of the cup used in this paper is Shore A 75, which is offered by the manufactory “Chengde Katop Equipment Manufacturing Co. Ltd.” In Liu et al., the parameters $C_{10}$ and $C_{01}$ can be determined according to the Shore hardness test of the cup. Because the hardness of the cup we use is the same as that of the cup in Liu et al., which is Shore A 75. Therefore, we directly use the values of $C_{10}$ and $C_{01}$ in Liu et al., the value of $C_{10}$ is 0.944, and the value of $C_{01}$ is 0.236.

$$W = C_{10}(I_1 - 3) + C_{01}(I_2 - 3).$$

where $W$ presents the strain energy density function; $C_{10}$, $C_{01}$ are the Rivlin coefficients and $I_1$, $I_2$ are the first and second Green invariants, respectively.

The calculation accuracy of hexahedral mesh is much higher than that of tetrahedral mesh. So, the sweeping method which is appropriate for generating the hexahedral mesh was adopted. However, the whole model, consisting of a pipe, cup, spacer, and mandrel, is an annular structure. The sweeping method cannot generate hexahedral mesh for annular structures. So, the whole model was sliced in the ZX plane. And then the hexahedral mesh can be generated. After slicing, the part of the pipe formed a new part and the other parts formed a new part. So, though the whole model was sliced, each part is still integrated into the calculation process. In this case, the deformation and stress of the pipe are not calculated, the pipe is set as a rigid body to reduce the amount of calculation. The hexahedral meshes were generated under the control of body sizing. The element size of PIG, consisting of a cup, a mandrel, and two spacers, was defined as 3 mm and the element size of the pipe was defined as 10 mm in meshing, and the model consists of 27,382 nodes and 23,226 elements. The FE model is shown in Figure 13, and the coordinate origin was set at the centers of the pipe inlet.

![Finite element model of pipe and cup](image)

**Figure 13** Finite element model of pipe and cup

![The edge node and fit circle with interference δ](image)

**Figure 14** The edge node and fit circle with interference $\delta$: (A) $\delta = 1.15\%$, (B) $\delta = 2.14\%$, (C) $\delta = 3.14\%$, and (D) $\delta = 4.16\%$.

**Table 4** Circumferential deformation of the cup

| Interference (%) | Radius of cup (mm) | Radius of fitting circle (mm) | Circumferential deformation (mm) |
|------------------|--------------------|-------------------------------|---------------------------------|
| 1.15             | 105.2              | 103.28                        | 1.92                            |
| 2.14             | 105.2              | 101.79                        | 3.41                            |
| 3.14             | 105.2              | 100.34                        | 4.86                            |
| 4.16             | 105.2              | 98.72                         | 6.48                            |
3.2 Boundary conditions

The pipe can be considered fixed and has no axial displacement during pigging. So, the “rigid body constraint” was applied to the pipe to fix the pipe in this simulation. As we all know, the cup is fixed on the mandrel through a spacer, flange, bolts, and nuts. The deformation of the cup only occurs in the lip of the cup. To reduce the amount of

| Interference (%) | Experimental result (mm) | Simulation result (mm) | Relative error (%) |
|------------------|--------------------------|------------------------|--------------------|
| 1.15             | 2.18515                  | 1.92                   | 12.13              |
| 2.14             | 4.121                    | 3.41                   | 17.25              |
| 3.14             | 4.94535                  | 4.86                   | 1.73               |
| 4.16             | 6.2006                   | 6.48                   | 4.51               |

**TABLE 5** Relative error between experimental and simulation result

![Displacement nephograms](image)

**FIGURE 15** The displacement nephograms in Z direction with interference $\delta$: (A) $\delta = 1.15\%$, (B) $\delta = 2.14\%$, (C) $\delta = 3.14\%$, and (D) $\delta = 4.16\%$. 
calculation, the 3D FE model established in this paper is a simplified model. As the fixed part will not deform, the cup, spacers, and mandrel are formed a part and the cup will not separate from the spacers and mandrel. Different from tie constraint, this way will make no contact between the cup and spacers and can reduce the calculation between the contact surface between the cup and spacers. In addition, since the cup and spacers have formed a whole, the meshes of the contact area between the cup and spacers, which mesh nodes are shared.

LS-DYNA is a kind of explicit dynamic solver. It uses a central difference method to solve the dynamic problem. This method discretizes the dynamic analysis process into countless time intervals. The amount of calculation is directly proportional to the time setting when using the LS-DYNA solver to solve the dynamic problem. So, to reduce CPU time as soon as possible, the time setting is usually no more than 1 s. The setting of time and displacement directly affects the speed of PIG. When the cup enters the pipe completely, it can be considered that the deformation of the cup reaches the top. So, the displacement applied to the cup only needs to make the cup enter the pipe completely. So, the “Remote Displacement” was applied to the surface of the spacer and the speed of PIG is uniform. A displacement of $-150$ mm in the $Z$ direction was applied to the surface of the spacer, which is coinciding with the direction of motion in the experiment and restricts the rotation in $X$, $Y$, and $Z$ directions, respectively.

Due to the uniform linear motion, the cup is in a state of force balance when the cup enters the pipe completely. So, the deformation and stress distribution of the cup is independent of the speed. So, the time value will not affect the simulation results. During the process of simulation, when the time is set to 0.1 or 0.2 s, the speed of PIG is very large. If the speed is too large, the cup will have a huge impact at the moment of contact with the pipe and the mesh on the contact area will fail. When the time setting is greater than 0.3 s, the deformation and effective stress change little after the cup enters the pipe completely, while the calculation time increases greatly. After comprehensive consideration, the time is set to 0.3 s.

During the simulation, the cup will contact the inner wall of the pipe, so define the contact between the cup and the pipe as “Contact Automatic Surface to Surface.” The static friction coefficient is 0.4 and the dynamic friction coefficient is 0.3. The sliding contact penalty coefficient was set to 0.2 for simulation. The above parameters were modified in the K file, generated by Workbench 19.2.

### 4 | VERIFICATION OF THE 3D FE MODEL

In section “boundary condition,” a displacement of $-150$ mm in $Z$ direction was applied to the surface of the spacer. To obtain the diameter of the cup edge more accurately, the $X$ and $Y$ coordinates of 84 nodes on the edge of the cup surface were extracted. The coordinates of 84 nodes were imported into Origin 2018 and fitted with a circle function. All fitting result shows that, as shown in Figure 14A–D, the diameter of the fitting circle does not equal the inner diameter of the pipe and is smaller than the diameter of the inner pipe. It can be verified that the edge of the cup is not close to the inner wall. The difference between the diameter of the fit circle and the diameter of the cup can be regarded as circumferential deformation. Through calculation, the circumferential deformation of the cup with various interference is shown in Table 4.

By comparing the experimental results with simulation results, as shown in Table 5, it can be observed that the relative errors on the circumferential deformation (the maximum relative error is 17.25%) all meet the engineering requirements (The maximum allowable error in pigging engineering is 20% according to the rule of thumb$^{14}$).

It can be seen from the displacement nephograms in the $Z$ direction, as shown in Figure 15A–D, that the displacement of the edge is not $-150$ mm. If the cup is not deformed in the axial direction, the displacement in the $Z$ directions should be $-150$ mm. So, the difference is the axial deformation. The axial deformation is shown in Table 6. By comparing the experimental results with simulation results, it can be observed that the relative errors in axial deformation (the maximum relative error is 13.49%) all meet the engineering requirements.

In conclusion, the relative errors between the simulation results and the experimental results are all small and can meet the engineering requirement no matter circumferential deformation or axial deformation. The 3D FE model and calculation method are reasonable and the parameters of the Mooney–Rivlin model provided are suitable for cup material in this paper.

### 5 | DEFORMATION ANALYSIS OF CUP WITH VARIOUS INTERFERENCE

Keep the FE model of the cup unchanged, and continue to reduce the pipe inner diameter (the pipe inner diameter is 200, 198, 196, and 194 mm, the interference is 5.20%, 6.26%, 7.35%, and 8.45%, respectively) and carry out FE simulation, so that it not only can obtain the deformation of the cup with
various interference but also can save the experimental cost. Extract the X and Y coordinates of 84 nodes on the edge of the cup and fitted with the circle function. The fitting results are shown in Figure 16A–D. The difference between the radius of the fitting circle and the original radius of the cup is the value of circumferential deformation. Combined with the results in Table 4, the results of the circumferential deformation with different interference are listed in Table 7. The simulation result shows that the value of circumferential deformation increases linearly with different interference and the fit curve can be expressed as Equation (7), as shown in Figure 17.

\[ y = 1.45983x + 0.30445, \]  

where \( x \) presents interference (%), \( y \) presents circumferential deformation (mm).

The displacement nephograms of the cup in the Z direction with various interference are shown in Figure 18A–D. Same with the above results, the maximum displacement in Z direction occurs at the

| Interference (%) | Experimental result (mm) | Simulation result (mm) | Relative error (%) |
|------------------|--------------------------|------------------------|-------------------|
| 1.15             | 1.4228                   | 1.5                    | 5.43              |
| 2.14             | 2.3901                   | 2.6                    | 8.78              |
| 3.14             | 3.6125                   | 4.1                    | 13.49             |
| 4.16             | 5.5371                   | 5.6                    | 1.14              |

**TABLE 6** Axial deformation of the cup.

| Interference (%) | Original radius (mm) | Fit radius (mm) | Circumferential deformation (mm) |
|------------------|----------------------|----------------|---------------------------------|
| 1.15             | 105.2                | 103.28         | 1.92                            |
| 2.14             | 105.2                | 101.79         | 3.41                            |
| 3.14             | 105.2                | 100.34         | 4.86                            |
| 4.16             | 105.2                | 98.72          | 6.48                            |
| 5.20             | 105.2                | 97.31          | 7.89                            |
| 6.26             | 105.2                | 95.63          | 9.57                            |
| 7.35             | 105.2                | 94.06          | 11.14                           |
| 8.45             | 105.2                | 92.78          | 12.42                           |

**TABLE 7** Circumferential deformation of the cup.

**FIGURE 16** The edge node and fit circle with interference \( \delta \): (A) \( \delta = 5.20\% \), (B) \( \delta = 6.26\% \), (C) \( \delta = 7.35\% \), and (D) \( \delta = 8.45\% \).

**FIGURE 17** The relationship between interference and circumference deformation.
FIGURE 18  The displacement nephograms in Z direction with interference \(\delta\): (A) \(\delta = 5.20\%\), (B) \(\delta = 6.26\%\), (C) \(\delta = 7.24\%\), and (D) \(\delta = 5.45\%\).

| Interference (%) | Applied displacement (mm) | Edge displacement (mm) | Axial deformation (mm) |
|------------------|---------------------------|------------------------|-----------------------|
| 1.15             | 150                       | 148.5                  | 1.5                   |
| 2.14             | 150                       | 147.4                  | 2.6                   |
| 3.14             | 150                       | 145.9                  | 4.1                   |
| 4.16             | 150                       | 144.4                  | 5.6                   |
| 5.20             | 150                       | 142.6                  | 7.4                   |
| 6.26             | 150                       | 139.9                  | 10.1                  |
| 7.35             | 150                       | 137.5                  | 12.5                  |
| 8.45             | 150                       | 136.3                  | 13.7                  |

TABLE 8  Axial deformation of the cup
The difference between the displacement at the edge of the cup and the setting displacement is the axial deformation of the cup. Combined with the results in Table 6, the results of the axial deformation with various interference are listed in Table 8. The relationship between axial deformation and interference can be expressed as Equation (8), as shown in Figure 19. The coefficient of determination ($R^2$) equals 0.99315, which indicates that the model has a high fitting degree.

$$y = 1.0085x^{1.23749}, \quad (8)$$

where $x$ presents interference (%), $y$ presents axial deformation (mm).

### 6 | NUMERICAL SIMULATION OF STRESS ON THE CUP

The distribution of stress of the cup is very complex, and it not only affects the cleaning ability of the cup, but also affects the failure of the cup leading to the stuck of PIG. According to the “PIG” principle, the power of PIG comes from the fluid pressure difference. So, only when the contact between the cup and the inner wall of the pipe is close tightly can the cup serves as a seal. Then, the PIG can run successfully in the pipe. Different to the research of Cao et al., the cup selected in this paper whose edge is not close to the pipe due to the combined action of external force of the pipe wall and the friction force during the experiment. Therefore, the stress distribution on the edge of the cup cannot be used to evaluate the contact status of the cup. The elements which are close tightly with the pipe wall must be accurately extracted. The nodes on the edge in ZX plane were extracted, as shown in Figure 20. There is no doubt that if the element was close tightly with the pipe wall, the $X$ coordinate of the node must equal to the radius of the pipe. Due to the element is very small, there are more than two nodes can meet the requirement. The area composed of two curves where the two nodes are located can be regarded as the area where the cup is close tightly to the pipe wall. To explore the stress distribution of the contact area of the cup, eight locations, as shown in Figure 21, were marked as $0^\circ$, $45^\circ$, $90^\circ$, $135^\circ$, $180^\circ$, $225^\circ$, $270^\circ$, and $315^\circ$, respectively.
The relationship between effective stress and time with various interference values. (A) $\delta = 1.15\%$, (B) $\delta = 2.14\%$, (C) $\delta = 3.14\%$, (D) $\delta = 4.16\%$, (E) $\delta = 5.20\%$, (F) $\delta = 6.26\%$, (G) $\delta = 7.35\%$, and (H) $\delta = 8.45\%$. 

**FIGURE 22** The relationship between effective stress and time with various interference values. (A) $\delta = 1.15\%$, (B) $\delta = 2.14\%$, (C) $\delta = 3.14\%$, (D) $\delta = 4.16\%$, (E) $\delta = 5.20\%$, (F) $\delta = 6.26\%$, (G) $\delta = 7.35\%$, and (H) $\delta = 8.45\%$. 


The contact between the cup and the pipe is a complex dynamic problem. Due to the hyper elasticity of the cup material, the value of effective stress is not a constant value. The relationship between effective stress and time with various interference values are shown in Figure 22A–H. The curves presented in figures indicate that the process of the cup passing through the pipe can be divided into three stages: (1) start-up stage (about 0–0.05 s), (2) contact stage (about 0.05–0.1 s), (3) stable stage (about 0.1–0.3 s).

The results indicated that in the start-up stage, though the cup does not contact with the pipe, the effective stress is very small due to the inertial force. When the cup just touched with the pipe, it enters the contact stage. The pipe had a great impact on the cup and the effective stress increased suddenly and sharply. When the cup enters the pipe completely, it enters the stabilized stage. The effective stress drops suddenly and then the value of effective stress tends to be stable.

From the amplitude of effective stress fluctuation, the stress fluctuation is very small when $\delta = 3.14\%, 4.16\%, 5.20\%, \text{ and } 6.26\%$. It shows that the contact state between the cup and pipe wall is perfect. When $\delta = 1.15\%$ and $2.14\%$, the fluctuation increased slightly. This is because the interference is small and the pipe has insufficient restrictions on the cup. When the $\delta = 7.35\% \text{ and } 8.45\%$, the fluctuation is very large. With the increase of interference, the deformation of the cup becomes larger and the cup wants to restore its shape under the action of elastic shape leading to the unstable of the effective stress. The stability of effective stress can reflect the working state of the cup during pigging. The more stable the effective stress, the less likely the cup is to be stuck, the longer the serve life, and the better the cleaning effect. So, for the cup studied in this paper, it can perform better with interference between $4\% \text{ and } 7\%$.

A moment within 0.2–0.3 s was selected to study the effective stress on the contact area. In this moment, the cup has been entered into the pipe completely and the various states also tend to stable. The value of effective stress of the contact area at eight locations were extracted, and then averaged, respectively. Average the average effective stress at eight locations, the value can be regarded as the effective stress on the contact area between the cup and pipe wall during the process of pigging. The results are shown in Table 9.

**TABLE 9** The effective stress on the contact area

| Interference (%) | Average effective stress (MPa) |
|------------------|-------------------------------|
| 1.15             | 0.103                         |
| 2.14             | 0.181                         |
| 3.14             | 0.236                         |
| 4.16             | 0.341                         |
| 5.20             | 0.348                         |
| 6.26             | 0.409                         |
| 7.35             | 0.555                         |
| 8.45             | 0.584                         |

![Figure 23](image.png) The relationship between interference and effective stress.

The obtained data was fitted nonlinearly because the contact behavior between the cup and pipe wall is nonlinear. The fitting curve can be described as Equation (9). The coefficient of determination ($R^2$) equals 0.96146, which indicates that the model has high fitting degree.

$$f(x) = 1 - e^{-0.09544x}, \quad (9)$$

where $x$ presents interference (%), $f(x)$ presents effective stress (MPa).

7 | CONCLUSIONS

In this paper, a method that can be carried out to measure the deformation of the cup utilizing the scanner based on reverse measurement was introduced. To obtain the accurate cup model, the point cloud data of the cup was obtained by the scanner. Compared with the model obtained by traditional methods, the model is more accurate, especially on the curved surface. In addition,
the relationship between interference and circumferential deformation, axial deformation, and effective stress on the contact area were obtained by simulation calculation. The results obtained from this study can provide guidance for the selection and design of the cups to avoid cup failure. The method for measuring the deformation of cups based on reverse measurement can solve the problem of the measurement of cup deformation. It also provides a novel FE simulation verification method in the field of pigging. The 3D FE model for the investigation of deformation and effective stress can help researchers understand the complex behavior of PIG. Some conclusions can be obtained as follows.

(1) It is feasible to carry out the method of comparing the point cloud data to measure the deformation of the cup, which can hardly be measured by the traditional method. The relationship between the interference and deformation shows that the value of circumferential deformation increases linearly with different interference, while the relationship between the interference and axial deformation is nonlinear.

(2) The 3D FE model can clearly present the effective stress on the contact area, which can hardly be obtained by the 2D FE model. In addition, using the LSDYNA solver to solve the nonlinear contact problem, the calculation results are easier to converge and the calculation time is short. According to the simulation results, the change of effective stress on the contact area can be divided into three stages: (a) start-up stage, (b) contact stage, (c) stable stage. From the amplitude of effective stress fluctuation, it can be included that the cup can perform better with interference between 4% and 7%.

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ORCID
Zhong Chen http://orcid.org/0000-0001-5934-878X

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