Research on feasibility verification method of pipe bending angle correction

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Abstract. Certain types of rocket engine pipes can only be cut perpendicular to the axis when cutting margins. In order to verify whether the pipeline can achieve the cutting margin perpendicular to the axis by correcting the bend angle, and finally perform accurate assembly, a verification method based on SolidWorks to simulate the pipe shaping process is proposed. First, the pipe model was reconstructed by using the measurement data. Second, the lengths of the pipe segments, the angles between the line segments and the angles between adjacent surfaces were extracted. Third, the simplified pipe model and interface model were established and assembled in SolidWorks. Finally, the angle constraints of the adjacent surfaces were added, and the angle constraints of the line segments were released. According to the assembly results, the feasibility of solving the problem through shape correction was analysed. Experiments show that this method can effectively verify the feasibility of the shape of the elbow, and also provide the shape of the pipe after the correction and the angle of each elbow.

1. Introduction

The pipeline components composed of various pipes undertake important tasks such as gas and liquid transportation in the rocket engine. The pipeline is one of the most important components of the rocket engine [1]. The manufacturing error, assembly error, pipe bending manufacturing error and welding cumulative error of the rocket engine body will affect the precise connection of the pipe and the interface. At present, digital technology is widely used in the design and manufacture of rocket engines, but there are still some pipes in the workshop that are processed by on-site sampling, resulting in inconsistencies between the actual product and the design model [2]. In order to meet the requirements of assembly, the pipe usually has a cutting margin at both ends during manufacture. The cutting position can be determined after careful comparison and the margin is finally cut off [3].

In the research on the digital manufacturing of pipes, Yan Mao took the aircraft pipes as the object to carry out the research of digital models instead of physical samples, and realized the digital information transmission of pipe design, processing and testing [4]. Xueshan Bai integrated the pipe CATIA module design, knowledge base, CNC pipe bending processing and testing, and realized the digital manufacturing of aircraft pipes [5]. Yanhong Wang used a vector measuring machine to measure...
the pipe sample to extract information, and digitally process the pipe [6]. Jinquan Li imported the information about the installation boundary of the pipe on the arrow into the robot, and let the robot replicate the installation boundary of the pipe on the arrow to manufacture a digital sampling pipe that was separated from the arrow body [7]. In order to ensure the requirements of pipe assembly, some pipes can only be cut flat when cutting the margin, not horseshoes. For this type of pipe, a method for verifying whether the pipe can be flattened by bending the pipe is proposed, so that it can be accurately assembled with the interface. This method can also provide reference data for the subsequent correction of the pipe.

2. Main ideas

Use high-precision laser vector measuring equipment to accurately measure the space coordinates and axis vector of the interface on the engine to determine the space position of the pipe interface. A three-dimensional optical measurement system based on multi-eye vision is used to measure the finished pipe. The model of the pipe parts is reconstructed by the reverse design technology [8], which truly reflects the geometric characteristics of the pipe parts and restores the actual data of the pipe.

For this method, the shape of the interface and the radius of the pipe are unnecessary, and it is difficult to simulate the deformation at the corners of the pipe during the calibration. In order to reduce the complexity of simulation analysis and eliminate unnecessary factors in the model, we simplified the pipes and interfaces. The straight lines represent the axis of the interface. The reference planes perpendicular to the axis represent the end surface where the interface contacts the pipe. The central axis represents the pipe.

The process of pipe bending angle correction can be simplified as the angle change of the bending angle. By replacing the arc at the corner with an angle and changing the angle between the two straight lines, the correction process of the corner can be approximated. The corner can only be bent but not twisted, and the two adjacent straight lines are coplanar. Therefore, during the corner correction, the angle between the surface of the two adjacent straight lines and the surface adjacent to it always remains unchanged.

When removing the margin, the pipe is cut into a straight opening, which means that the axis of the two ends of the pipe coincides with the axis of the interface on both sides. Use the computer-aided design software SolidWorks to edit the model again. The pipe is divided into parts, the angle constraint of the adjacent line segments is cancelled, the relationship between the line and the surface is converted into a matching constraint, and then each part of the pipe and the interface are reassembled. According to the assembly results, the feasibility of correcting the bending part of the pipe can be intuitively analyzed.

3. Method introduction

The method is mainly to process the obtained data many times, extract the information and model again after simplifying the model features, and verify the feasibility of the pipe shape correction by setting the matching constraints in the assembly. The main process is shown in Figure 1.
The specific steps of the method are as follows:

1) Gain data. Obtain the coordinates of the central point of the welding end face of the interface and the pipe and the axial vector data of the interface. The three-dimensional optical measurement system based on multi-camera fusion reconstructs the 3D model of the pipe. The endpoint coordinates of the axis of each straight-line segment of the pipe are extracted from the model.

2) Build simplified models. Use line segments and surfaces to represent pipes and interfaces, and draw parts of interfaces and pipes respectively.

3) Process the pipe model and measure related angle information. Draw the extension lines of the adjacent straight-line segment, extract the coordinate information of the intersection point, and then measure the angle of the angle between the two straight lines. Add faces one by one and measure the angle between two adjacent faces.

4) Draw each straight-line segment separately using the original pipe data and the coordinates of the intersection point. Except for the two end points at both ends of the pipe, the middle end points are replaced by the nearest intersection points to reconstruct the straight-line model of the pipe.

5) Create an assembly. Insert a simplified model of the interface and each section of the pipe. Add a fit to connect each straight-line segment in sequence. Set the angle between adjacent faces.

6) Add a fit to make the axis of the straight line at both ends of the pipe coincide with the axis of the two interfaces respectively. If the cooperation is successfully added, move the pipe to change its posture. Comprehensive consideration of the shape and margin of the duct, select a more ideal posture, and measure the margin at both ends of the duct and the angle of each bend. This can provide a reference for subsequent pipe repair work. If the matching addition fails, it means that the pipe cannot be elbow-shaped to achieve the purpose of cutting the straight opening to remove the margin for assembly.
4. Experiments

4.1. Pipe introduction
Use this method to verify a certain pipe to analyse the feasibility of this method. The pipe has four bends and five straight sections. Both ends of the pipe need to be precisely assembled with the two interfaces on the engine. When designing and processing, the two ends of the pipe have been reserved for cutting allowance. The design model of the pipe is shown in Figure 2.

![Figure 2. Pipe design model used in the experiment.](image)

The condition for removing the excess of the pipe through the straight cut is that the axis of the straight section at both ends of the pipe coincides with the axis of the two interfaces. After correctly matching one end of the pipe with one side of the interface, it is found that the straight section at the other end of the pipe is parallel to the axis of the interface, and the distance is 13.99mm, which cannot be directly assembled. Figure 3 is a mock assembly drawing of the pipe.

![Figure 3. Key information of simplified pipe and interface model.](image)

4.2. Key steps for instance verification
After extracting the key information of the pipe and the interface, a simplified model is established, as shown in Figure 3. Draw the extension line of the axis of each straight-line segment of the pipe, mark and extract the coordinate information of the intersection of the extension line. These points are point 1, point 2, point 3 and point 4 respectively. Measure and record the angle between the extension lines. Respectively draw the planes where the adjacent straight-line segments are located, which are plane 1, plane 2, plane 3 and plane 4. Then measure and record the angles between the plane and the other plane respectively, which are plane 1 and plane 2, plane 2 and plane 3, plane 3 and plane 4, respectively.
The four intersection points of the extension line are used to replace the adjacent straight end points respectively, and the simplified model of the pipe is drawn in sections and assembled. Add mates so that the endpoints of adjacent straight lines coincide. Set the angle of the adjacent plane to release the angle constraint of the adjacent straight-line segment.

4.3. Results and discussion
After adding the corresponding mates in the assembly, the assembly is under-defined and there is no conflict between the mate settings. This shows that the pipe can realize the collinear fit between the straight sections at both ends of the pipe and the axis of the interfaces at both ends by changing the angle of the bend angle. This means that it can meet the needs of removing the cut straight opening. By moving the pipe model to change the shape of the pipe, six ideal pipe postures were found, as shown in Figure 4. We have considered the factors of the degree of change in the shape and the margin of the pipe.

Figure 4. Six ideal pipe model postures.
First measure the angle of the bend from left to right in the pipe model. Then measure the distance between the end of the pipe and the central point of the end face of the interface. The statistical results are shown in Table 1.

| Model | Angle 1 (deg) | Angle 2 (deg) | Angle 3 (deg) | Angle 4 (deg) | Length 1 (mm) | Length 2 (mm) | Mean |
|-------|---------------|---------------|---------------|---------------|---------------|---------------|------|
| 0     | 83.96         | 117.18        | 168.99        | 128.02        | -3.89         | 1.21          | 142.13|
| 1     | 145.16        | 146.3         | 134.77        | 68.67         | -29.61        | -35.58        | 139.67|
| 2     | 145.2         | 146.38        | 158.99        | 92.95         | 8.99          | -12.46        | 144.58|
| 3     | 129.03        | 108.39        | 138.38        | 117.04        | 10.82         | -8.73         | 137.89|
| 4     | 143.9         | 123.6         | 167.63        | 89.33         | 0             | 0             | 143.23|
| 5     | 149.84        | 145.77        | 134.11        | 67.89         | 2.54          | -17.27        | 147.56|
| 6     | 139.67        | 123.6         | 152.99        | 119.51        | -1.85         | -12.13        | 138.18|

In the data representing the distance in the table, there are positive and negative numbers. The negative number refers to the length of the pipe that needs to be cut off. A positive number means that the adjusted pipe length is insufficient and needs to be increased.

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Calculate the angle change rate of each model relative to the original model. Draw a line graph to analyze the degree of change of the bending angle during the correction. A positive rate of change indicates that the corner angle becomes larger, and a negative rate of change is the opposite. It can be seen from Figure 5 that the change of angle 1 is the largest during the calibration, and the average change rate is about 70%. The effect of angle 1 on the performance of the pipe should be paid attention to during the calibration. The absolute value of the mean value of the rate of change of angle 2 and angle 3 is within 20%, and the variance is small, and the bending pipe shaping has little effect on its performance. The variance of angle 4 is relatively large, so it needs to be analyzed with other angles. The rate of change of angles 2, 3, and 4 of model 3 and model 6 are all within 20%, and the rate of change of angle 1 is correspondingly smaller than that of the other four models, and the margin that needs to be cut or supplemented is also within 20mm. These two models are the most ideal two of the six models, and these two schemes can be given priority when shaping. In the corner correction, if the angle changes too much, the pipe may suffer fatigue fracture and other defects. Therefore, the change data of the bend angle can provide a reference for the subsequent correction of the pipe.
5. Conclusions
The process of bending the pipe can be transformed into the change of the bending angle. Two adjacent line segments are coplanar, and the angle between adjacent faces is always the same. Release the angle constraint of the bent part of the pipe so that it can be changed. Measure and set the angle of the adjacent surface to ensure that the pipe changes in the correct way during the simulation calibration. By extracting data from the pipe model in SolidWorks, rebuild simplified models and assemble them. Use the constraint relationship in the assembly to determine whether the pipe can be cut perpendicular to the axis to remove the margin. It is a novel method for solving the problem of pipe assembly. Judging from the results of the example verification, this method can not only effectively verify the feasibility of the pipe alignment, but also provide reference data for subsequent pipe alignment and repair. It can not only reduce the cost of pipe manufacturing, but also shorten the assembly cycle of the engine.

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