The Design and Analysis of Free Bending Tube Bending Machine

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Abstract. The existing devices for the 3D tube bending normally are complex on the mechanism and unmanageable. In this study, a new kind of tube bending machine which can realize the free bending in space through using the principle of superimposing two main parts, which provide more degree of freedom for the new developed machine. Screw system is established based on screw theory, then the analysis about the degree of freedom of each main part and the overall mechanism has been conducted.

1. Introduction

In addition to good processing and forming properties, the tube material has the characteristics of high strength stiffness and high material utilization. The demand for high quality and high-precision tube bender is increasing, and owing to excellent characters like high strength and stiffness and high efficient utilization, the bent tube have an important application in many fields of national production, such as the furniture, fluid arrangements, aviation, aerospace, automobile and precision machinery [1,2]. The bending process of the metal tube is one common forming process. The purpose of this process is translating the tube into the defined profile with specific bending curvature, angle and shape. Traditional bending methods of tubes include rotary-draw bending, press bending and roll bending [3].

Tube bender is the main mechanical equipment for tube bending process. At present, there are mainly CNC bending machine, press machine, roll bending machine, draw bender and so on. However, with the demand for complex spatial tube is increasing, there are lots of limitations in traditional tube benders which can only be fit for the profiles which have simple shapes and bend radii without continuous changing. The latest technology of 3D free forming can overcome the shortcomings above, and it can make tube shaped precisely in 3D space.

As the complex spatial tube has been successfully applied in material forming field, lots of design about the 3D bender for tube has been arising in recent years. This kind of technology makes use of the principle of the modeless forming and the hydraulic servo control technology, it uses servers to design radian of tube, and finally realize the control of final forming shape of tube. This kind of technology has changed traditional process of die forming of tube, and overcome the disadvantages and limitations of die forming which can make forming process flexible and convenient. It can also improve greatly the efficiency and precision of the production process.

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2. Principle of 3D free bending

The basic principle of bending is shown in Figure 1. The tube which is driven by a propulsion equipment through fixed die and mobile die. The mobile die can move and rotate in space. The move of mobile die can adjust distance V between the exit of the fixed die and the center of the mobile die and offset u between the center line of the fixed die and the center of the mobile die [4]. The rotation of the mobile die is to control the deflection angle of the mobile die θ . The movement and deflection of the rotary platform will exert a force on the tube. The translation and rotation of the mobile die will exert a pushing force, tube will be bent under the influence of this force as shown in Figure 1. The bending radius of the tube R is determined by distance V, offset u and deflection angle θ [5, 6]. The relationship between each parameter is as Eq. (1).

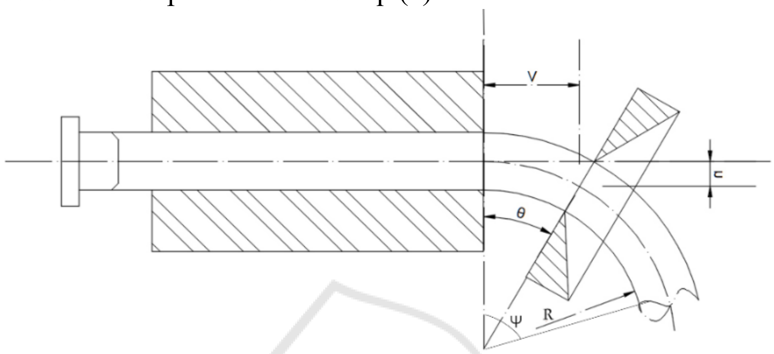

Figure 1. Principle of 3D free bending.

$$\begin{aligned} u &= R - \sqrt{R^2 - V^2} \\ \theta &= \arcsin \frac{V}{R} \end{aligned} \tag{1}$$

3. Design and analysis of new 3D bender

The new 3D bender referred in this article is shown in Figure 2. This device mainly includes four parts, they are feed mechanism, fixed die, translational part of mobile die and rotary part of mobile. The feed mechanism can clamp tube and push tube forward. The translational part of mobile die is a 3PUU structure, it can make the mobile platform move along any direction in space. The rotary part of mobile die which can make platform rotate is a 2RPS-RS structure.

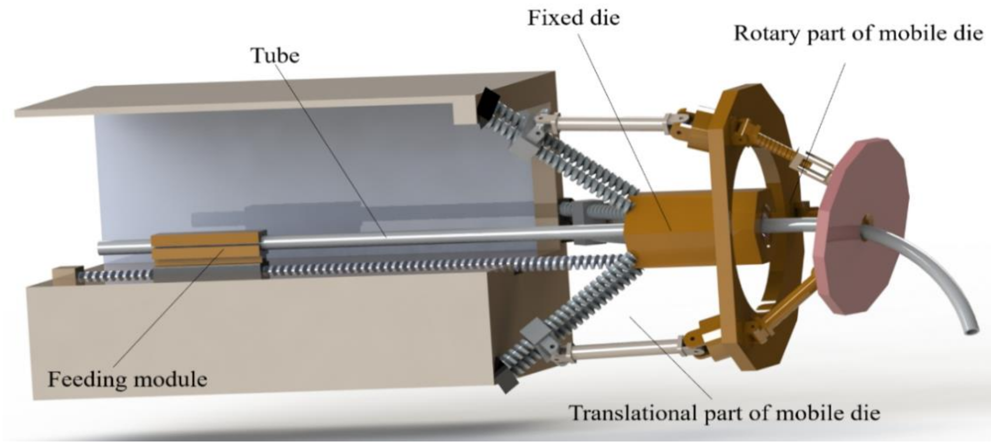

Figure 2. Global design of tube bending machine.

3.1. The analysis on degree of freedom of translational part

The 3PUU structure which is researched in this article has three parallel branched chains which are axial symmetrical distributed in space. On each branched chain, the two ends of the fixed length rod are connected to the moving platform and slider with the universal joint (U-joint), and slider can move on guide chase screw. These joints are connected in P-U-U order. Its structure chart is shown in Figure 3.

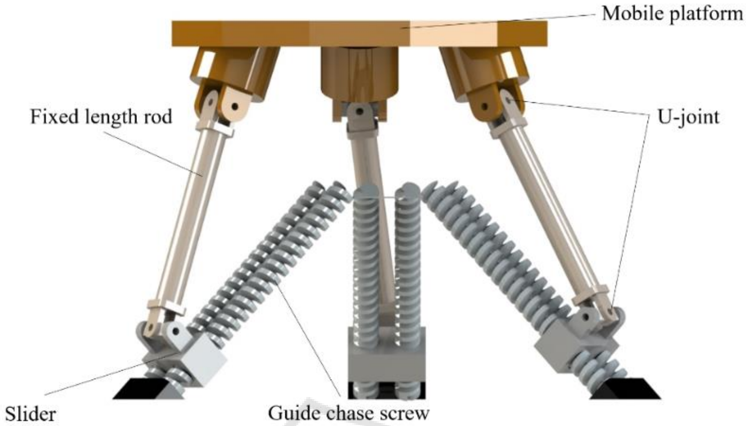

Figure 3. The translational part of mobile die.

Coordinate system is established as shown in Figure 4. X-axis and Y–axis are along the two axes of U-joint; Z- axis is perpendicular to crosshead plane of U-joint, it can be also said as Z- axis along the direction of fixed length rod. Under the initial assembly position, the screw system of each branch chain is as Eq. (2).

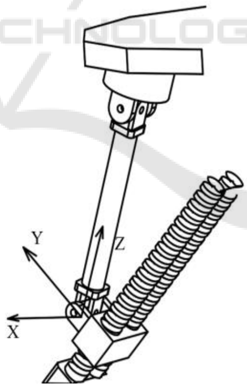

Figure 4. Coordinate system of branch chain.

$$\begin{cases} \$_1 = \begin{pmatrix} 0 & 0 & 0; & 0 & e_1 & f_1 \end{pmatrix} \\ \$_2 = \begin{pmatrix} 1 & 0 & 0; & 0 & 0 & 0 \end{pmatrix} \\ \$_3 = \begin{pmatrix} 0 & 1 & 0; & 0 & 0 & 0 \end{pmatrix} \\ \$_4 = \begin{pmatrix} 0 & 1 & 0; & d_4 & 0 & 0 \end{pmatrix} \\ \$_5 = \begin{pmatrix} 1 & 0 & 0; & 0 & e_5 & 0 \end{pmatrix} \end{cases} \tag{2}$$

To calculate reciprocal screw of five kinematic screw, all the variables in Eq. (2) are import into formulation $\$^r \circ \$_i = 0$ ($i = 1,2,3,4,5$), and the constraint screw of single branched chain is obtained as Eq. (3).

$$\$^r = \begin{pmatrix} 0 & 0 & 0; & 0 & 0 & 1 \end{pmatrix} \tag{3}$$

In Eq. (3), the first three elements of the constraint screw are all 0, so this screw is constrained couples. This couples limits the rotation around the *Z*-axis. Because of the symmetry of this structure, the screw system of the other two branched chains is the same as the first one, and their direction correspond to direction of respective fixed length rod. Because three couple of three symmetrical branched chain are not paralleled to each other and linearly independent, three independent constraints act on the mobile platform. These three constrained couples constrain three rotational freedom, so mobile platform has only three translational freedom. Therefore, mobile platform can move along *X*-axis, *Y*-axis, *Z*-axis and the direction of any linear combination of them.

Besides, the degree of freedom of this mechanism also be calculated by the G-K formulation. It is obvious that there are no common constraint and redundant constraints in this device. So the degree of freedom of this mechanism can be calculated by Eq. (4).

$$M = d\left(n - g - 1\right) + \sum_{i=1}^{g} f_i + v = 6 \times \left(8 - 9 - 1\right) + 15 + 0 = 3 \tag{4}$$

d— *Order of mechanism*

n—*The number of moving part in the mechanism*

g—*The number of kinematic pair*

fi—*The number of degree of freedom of kinematic pair*

v—*The number of redundant constraints*

The results of calculations is consistent with the theoretical analysis and confirm the correctness of the analysis.

3.2. The analysis on degree of freedom of rotary part

The 2RPS-RS structure which is researched in this article is shown in Figure 5. This device has three branched chains, two of them are the same. The lower end of the guide chase screw is connected to the moving platform with revolute (R-joint) and the upper end of the screw is connected to the rotary platform with sphere joint (S-joint) on these two branched chains. The third branched chain is that the lower end of fixed length rod is connected to mobile platform with revolute (R-joint) and the upper end of the rod is connected to the rotary platform with sphere joint (S-joint).

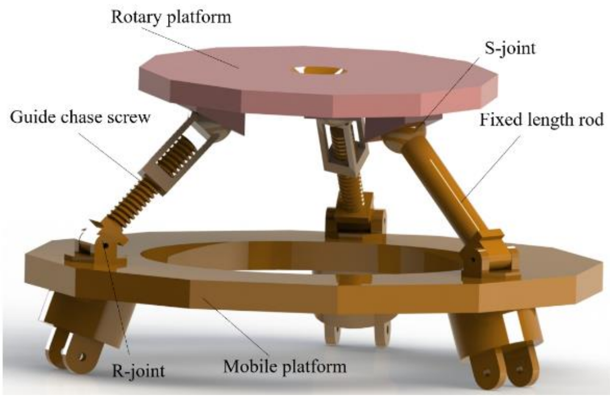

Figure 5. The rotary part of mobile die.

For the first branched chain, the coordinate system is established as shown in Figure 6. The origin is on the first kinematic pair, and X-axis is along the axis of this R-joint, and Z-axis is perpendicular to basic plane. So the screw system of this branch chain is as Eq. (5).

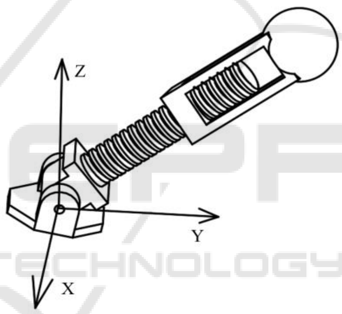

Figure 6. Coordinate system of first branch chain.

$$\begin{cases} \$_1 = (1 \quad 0 \quad 0; \quad 0 \quad 0 \quad 0) \\ \$_2 = (0 \quad 0 \quad 0; \quad 0 \quad \mathrm{e} \quad f) \\ \$_3 = (1 \quad 0 \quad 0; \quad 0 \quad f \quad -e) \\ \$_4 = (0 \quad 1 \quad 0; \quad -f \quad 0 \quad 0) \\ \$_5 = (0 \quad 0 \quad 1; \quad e \quad 0 \quad 0) \end{cases} \tag{5}$$

By the same method, the constraint screw of this branched chain can be received as Eq. (6)

$$\$^r = (1 \quad 0 \quad 0; \quad 0 \quad f \quad -e) \tag{6}$$

For the third branched chain, the coordinate system is established by the same way as shown in Figure 7. So the screw system of this branch chain is as Eq. (7).

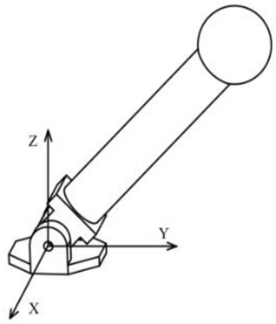

Figure 7. Coordinate system of third branch chain.

$$\begin{cases} \$_1 = (1 \quad 0 \quad 0; \quad 0 \quad 0 \quad 0) \\ \$_2 = (1 \quad 0 \quad 0; \quad 0 \quad f \quad -e) \\ \$_3 = (0 \quad 1 \quad 0; \quad -f \quad 0 \quad 0) \\ \$_4 = (0 \quad 0 \quad 1; \quad e \quad 0 \quad 0) \end{cases} \tag{7}$$

By calculating, two linearly independent constraint screws are obtained as Eq. (8).

$$\begin{cases} \$_1^r = (1 \quad 0 \quad 0; \quad 0 \quad f \quad -e) \\ \$_2^r = (0 \quad f \quad e; \quad 0 \quad 0 \quad 0) \end{cases} \tag{8}$$

For the rotary part, the first two chains have similarly constraining force. This force act on the rotary platform, and it is through the center of respective branched chain’s sphere joint and parallel to the axis of revolute joint. The third branched chain has two constraining force, one of them is same as force of the first two chains, the other one along the direction of fixed length rod. These four constraining force are linearly independent and they restrain four rotary platform’s degree of freedom. It is find that the three translations and a rotation around Z-axis of rotary platform are limited by analyzing. So rotary platform can only have two-dimensional rotation in the plane.

It is obvious that there are no common constraint and redundant constraints in this device. So the degree of freedom can also be calculated according to the G-K formulation as Eq. (9).

$$M = d(n-g-1) + \sum_{i=1}^{g} f_i + v = 6\times(7-8-1)+14 \tag{9}$$

The results of calculations is consistent with the theoretical analysis and confirm the correctness of the analysis.

4. Conclusions

A new kind of tube bending machine is proposed in this article for the demand of complex spatial tube is increasing significantly. The mobile die of this machine contains two parts, the one is a 3PUU translational part, the other one is a 2RPS-RS rotary part. By the analysis is based on screw theory, it is find that this 3PUU part has three translational degree of freedom, which means it can move along any direction in space. The 2RPS-RS rotary part has two rotational degree of freedom. After combining these two parts, the mobile die has five degree of freedom, the condition of free bending of tube will be satisfied. More complex spatial tube can be designed and manufactured by this new developed machine.

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