Analysis of the Influence of Tension on the Fiber Winding Track

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Abstract

In this paper, in order to solve the question of the winding tracks affected by tension leading to pipeline performance degradation, we analyze the tension on the wound composite pipes and establish a winding model about six degrees of freedom robotic arm and find the solver of the kinematic equations. We designed a winding track and established on a MATLAB and ADAMS co-simulation platform. The winding track affected by the tension is simulated. According to the results, we can obtain the force of the joints of the robot. Taking these force data as the compensation of the joint force, the robot can do the desired track overcoming the winding tension.

Keywords: winding track; tension; manipulators; dynamics; simulation analysis

1. Introduction

Compared with traditional materials, composites pipeline has a lot of advantages, such as corrosion resistant, light weight, high strength, easiness to scale, surface smoothness and so on, and in the areas of chemical, petroleum and water treatment is widely used [1]. In order to give full play to the advantages of glass fibers, the mainly processing methods is fixed-length reciprocating winding, and which is the method in which the fiber impregnated with resin is wound onto the mandrel with fixed-length along. The existing winding track is mostly designed according to the desired linear, in which winding tension affecting the trajectory is not considered, but in the winding process the tension will result in a different type of wrapping tightness of the pipe and thus affect the performance of the composite material, so to design the winding track considering the impact of tension is an important way to improve the quality of the pipe.

Currently, there are many CAD software of the winding track design, but most of them are only able to design pipes or pipe fittings with simple structure or shape, such as axisymmetric pipes. For the non-axisymmetric pipe fittings, such as the elbow, only the CADWIND [2] (developed by the University of Leuven) and CADFIL [3] (developed by the University of Nottingham) can design the fiber winding track. The Catholic University develops the PUMA-726 winding robot. The robot can design the winding track with the triangular patches approximation method [4], and inspect the quality of the pipe by using the ultrasonic. Test is needed to ensure the stability of the track designed with the method and the evenness of the fiber covering on the surface of the mandrel; actually it is a try and correction method [5]. In the Ottawa University of Canada, although B. Bernard. A. Fahim and M. Munro in the Department of Mechanical Engineering developed software for fiber winding, it can only wind the "T"-shaped tube. Using a patchwork of local triangle method is theoretically plausible, but this method separates the mandrel. None of these CAD / CAM software considers the impact of tension on the winding track. Plus, they are expensive, so they are more suitable for the scientific research, military, and some other special industries rather than manufactured in glass pipes enterprise promotion [6].

For the above shortcomings, the process of winding tension changes [7] is analyzed in this paper, taking into account the influence of the tension on the winding spatial trajectories, we build a mathematical model of manipulator kinematics [8] for use the six degrees-of-freedom manipulator, and use the MATLAB to design the wound track [9]. A co-simulation platform [10] of MATLAB and ADAMS is established, we can obtain the force of the joints of the robot. Taking these force data as the compensation of the joint force, the robot can do the desired track overcoming the winding tension so as to effectively improve the performance of composite pipes.

2. Analysis of Composite Pipe Winding Tension

In the composite pipe molding process, in order to make the tension meet the technical requirements, the friction or resistance must be applied on the composite material. This can be divided into two cases. First, the friction roller or a belt is put on the surface of the material during winding process to rotate with the mandrel and form the frictional force, and thereby forms the tension on the composite. In this case, the tension doesn't change with the radius of the yarn group. The system is simple, but for the differences in the nature of the composite material, the roll imposes the positive pressure and friction on the surface of material but not all the materials are applied.

Second, the drag torque is imposed on the unwinding roll by adding a device on the axis. In this case, if the torque keeps unchanged in the winding process, the tension on the composite pipe will change with the radius of the yarn group. Although this system is complex, because it is suitable for different kinds of material, it has been widely used. Most of the current tension winding machine control systems uses this manner.

As the tension of every place of the same fiber is during winding, taking unwinding roll side tension as the research object, the torque moment equilibrium equation is as shown.

$$\dot{J}\omega + J\dot{\omega} + F_0 R + M_0 + M_f = M \tag{1}$$

Among it:　J ——yarn groups present moment of inertia

F_0 ——default yarn tension

M_0 ——dry yarn friction torque

M ——control torque

ω ——the reel angular velocity

R ——the actual radius of yarn Group

M_f ——the viscous friction torque

It can be obtained from the equation torque that the tension of the filament winding process is affected by multiple variables and the system is a time-varying system. Because the instantaneous moment of inertia of the yarn group hardly changes, the $\dot{J}\omega$ impact of the tension can be ignored.

So the Equation 1 can be simplified as:

$$J\dot{\omega} = M - F_0 R - M_0 - M_f \tag{2}$$

From Equation 2, the tension of the fiber is mainly affected by the yarn group velocity and the radius of the yarn package. The current moment of inertia of the yarn groups' changes with the radius of the yarn, the relationship of yarn group inertia and radius is:

$$J = J_s + \frac{\pi B \rho}{2}(R^4 - R_{min}^4) \tag{3}$$

Among it:　J_s ——the current inertia of reel

B ——the width of yarn

ρ ——the density of yarn

R_{min} ——the least radius of yarn groups

The relationship of yarn group between the radius of the corner of yarn and yarn thickness is:

$$R = R_{max} - \frac{\delta}{2\pi}\theta \qquad (4)$$

Among it: R_{max} ——the maximum radius of yarn groups

δ ——the thickness of yarn

θ ——the rotation angle of yarn groups

The relationship of yarn speed angular velocity and the reel velocity is:

$$v = R\omega \qquad (5)$$

$$\omega = \frac{d\theta}{dt} \qquad (6)$$

For (4) derivative can be obtained:

$$\frac{d\theta}{dt} = -\frac{2\pi}{\delta}\frac{dR}{dt} \qquad (7)$$

$$\frac{d^2\theta}{dt^2} = -\frac{2\pi}{\delta}\frac{d^2R}{dt^2} \qquad (8)$$

The (7) (8) into (2) can be obtained:

$$\frac{d^2R}{dt^2} = -\frac{\delta}{2\pi J}(M - M_f - M_0 - F_0 R) \qquad (9)$$

The relationship between R and t can be obtained from the equations above. Taking the kinematic equation $\frac{d^2\theta}{dt^2} = \frac{v}{R^2}$ into Equation 9, we can get:

$$M - M_f - M_0 - F_0 R = J\frac{v}{R^2} \qquad (10)$$

Since M_f and M_0 so small that can be negligible, and then Equation 10 can be simplified as:

$$F_0 = \frac{2M - \pi B \rho v R^2}{2R} \qquad (11)$$

Equation 11 describes the relationship between the winding tension and the process parameters.

3. Establishment of Six Degrees of Freedom Manipulator Kinematics Equations and Mathematical Models

3.1. Establishment the Mathematical Models

The movement of the robot arm mainly depends on control kinematics, and motion kinematics accuracy mainly depends on the choice of the mathematical model. The six degrees-of-freedom robotic arm used in this paper is the MOTOMAN made by the YaskawaCo. The classic D-H notation mathematical model is adopted to build the model of this robot. D-H notation was proposed in a paper published in 1955 ASME Journal of Applied Mechanics by Denavit and Hartenberg. With the kinematic equations obtained, D-H notation has now become the standard means of the robot modeling. The basic principle of the D-H notation is to provide a supporting structure of the links and the joints and then the matrix is established of the local coordinate system. To describe the

use of homogeneous coordinates of each link arm geometry and the reference coordinate space, we use the 4x4 homogeneous transformation matrix to describe the two adjacent Links i and i-1 space geometry, and deduce the relative of the spatial pose of the reference coordinate system between the end of the robotic arm and the local coordinate system.

The MOTOMAN robot is six degrees-of-freedom of space position, including six rotational joints and six links. The part between the first rotating part of the joint and the grounds is called the base. The base connects Link 1 by rotating Joints 1. Link 1 and Link 2 are connected by rotating Joints 2, and so on. Using the D-H notation to model of the robot arm, the coordinate system is shown in Figure 1.
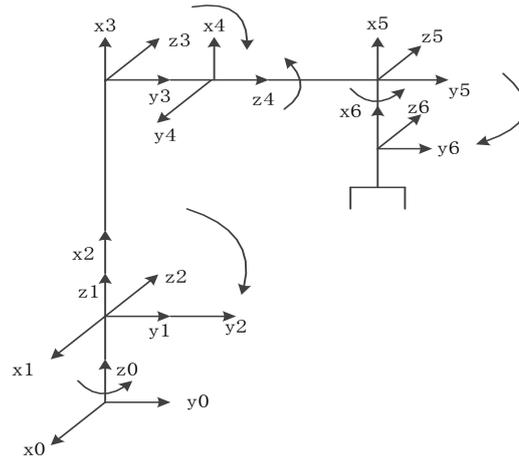
Figure 1. The Coordinate of the Manipulator

The angles of the six rotational joints of the arm are $\theta_1 \sim \theta_6$. The length of six links is $a_1 \sim a_6$. Supposing the link coordinate system is determined, the coordinates between i and i-1 can be described by the coordinate transformation matrix Equation 12.

$$T_i^{i-1} = \begin{bmatrix} c_i & -s_i & 0 & a_{i-1} \\ s_i c(\alpha_{i-1}) & c_i c(\alpha_{i-1}) & -s(\alpha_{i-1}) & -a_i s(\alpha_{i-1}) \\ s_i s(\alpha_{i-1}) & c_i s(\alpha_{i-1}) & c(\alpha_{i-1}) & a_i c(\alpha_{i-1}) \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{12}$$

Among it: $c_i = \cos\theta_i$

$\quad s_i = \sin\theta_i \, i = 1,2,3\ldots n$

Substituting the six joints' parameters into Equation 12, the coordinate transformation matrix between the adjacent lines can be obtained, shown as follows:

$$T_2^1 = \begin{bmatrix} c_1 c_2 & -c_1 s_2 & s_1 & c_1 \\ s_1 c_2 & -s_1 s_2 & -c_1 & a_1 s_1 \\ -s_2 & -c_2 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}; \; T_3^2 = \begin{bmatrix} c_3 & -s_3 & 0 & a_2 \\ s_3 & c_3 & 1 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}; \; T_4^3 = \begin{bmatrix} c_4 & -s_4 & 0 & a_3 \\ 0 & 0 & 1 & 0 \\ -s_4 & -c_4 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$T_5^4 = \begin{bmatrix} c_4 c_5 & -c_4 s_5 & s_4 & 0 \\ s_5 & c_5 & 0 & a_4 \\ -s_4 c_5 & s_4 s_5 & c_4 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}; \; T_6^5 = \begin{bmatrix} c_6 & -s_6 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ s_6 & c_6 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{13}$$

3.2. Kinematic Equation Solver

Kinematic equations are divided into positive and negative solution. Using every joint motion parameter variables $\theta_1 \sim \theta_6$ to solve robot pose related to the end of the reference coordinate system is called the positive solution; using the end of the robot that meets the job requirements related to the reference coordinate system of the position and pose to solve each joint motion parameters $\theta_1 \sim \theta_6$ is called the negative solution.

The transformation matrix between Coordinate n and Coordinate 1 can be obtained by the multiplied adjacent coordinate transformation matrixes:

$$T_6^1 = T_2^1 T_3^2 T_4^3 T_5^4 T_6^5 \tag{14}$$

The Equation 14 is a function including all variables of the joint. If every joint is assigned, the pose of Link 6 can be deduced. The positive solution can be obtained by the Equation 14:

$$T_6^1 = \begin{bmatrix} n_x & o_x & a_x & p_x \\ n_y & o_y & a_y & p_y \\ n_z & o_z & a_z & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{15}$$

The kinematic positive and negative solution is inverse solving. By multiplying $\left(T_2^1\right)^{-1}$ on both sides of equation 15, equation 16 can be obtained:

$$\left(T_2^1\right)^{-1} T_6^1 = T_3^2 T_4^3 T_5^4 T_6^5 \tag{16}$$

That is:

$$\begin{bmatrix} c_1 c_2 & s_1 c_2 & 0 & 0 \\ -c_1 s_2 & -s_1 s_2 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} n_x & o_x & a_x & p_x \\ n_y & o_y & a_y & p_y \\ n_z & o_z & a_z & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix} = T_3^2 T_4^3 T_5^4 T_6^5 \tag{17}$$

Making the both sides' individual elements of Equation 17 equal, we can find the first rotating joint angle θ1. In a similar way can we get the rest of the rotating joint angle $\theta_2 \sim \theta_6$.

4. Design of Manipulator Simulation Model

The manipulator consists with base six rotating joints and six links. The simulation model is built according to the established coordinate system as shown in Figure 2.
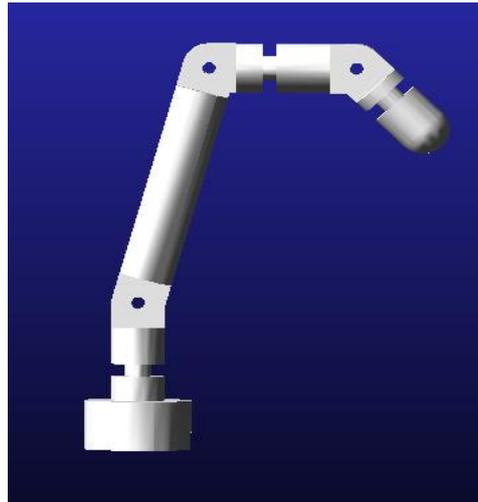
Figure 2. The Simulation Model of Manipulator

As is shown in Figure 2, the part fixed on the ground is the base. Link 1 is placed on the base, and Link 1 is connected to rotating Joint 1, and so on. The length of Link 1, 3, 5 is 200 cm, Link 2 is 800 cm, Link 4 is 300 cm, and Link 6 is 200 cm. The direction of the global coordinate system of the robot arm is the same as the local Coordinate 1, setting on the base. The direction of gravity is the −Y axis. The model uses the rigid material. It makes the maximum guarantee to keep model less prone to deformation characteristics.

5. Manipulator Model Simulation and Analysis

5.1. The Model Building

ADAMS(Automatic Dynamic Analysis of Mechanical Systems) is a software which means dynamics of mechanical systems automatically analyze, this software is a virtual prototype analysis software that is developed by the United States MDI (Mechanical Dynamics Inc), and in the aspect of mechanical system simulation software it was widely used. Although ADAMS has a very strong function of the kinematics and dynamics solver, but its disadvantage is built the physical modeling, for the simple part use ADAMS modeling tool to establish but the model is also very rough; for the complex parts we are usually use the solid modeling software which has powerful features for modeling, such as PRO / ENGINEER Wildfire, SOLIDWORKS, CAXA *etc.*, then the model is directly carried into ADAMS solver. Since the robotic is six degrees-of-freedom mechanical structure, and composes with the base, six rotating joints and six links, the structure is very complex, so in this paper the model is built by the PRO / ENGINEER Wildfire software.

At first, each part of the model was built in PRO / ENGINEER Wildfire 5.0 according to the established coordinate system, every local coordinate system of the model is match with the corresponding coordinate system, the parts were saved as the part format generated; then a component file was created in the PRO/ENGINEER Wildfire, the base part as the basis of complete mechanical arm model was imported to component files, then the rest of the model are imported according to the connection sequence, and then all the parts were combined by the PRO / ENGINEER Wildfire's assembly functions, and the angle of each joint was adjust, in order to make the robotic model match the actual robot, the assembly model was saved as model__out.log.1; finally, in order to facilitate the full model import into ADAMS, so the file was saved as a copy of Parasolid format model__out.log.1 which ADAMS can better identify.

5.2. The End of the Robot Trajectory Planning

In this paper, the MATLAB was used to design the trajectory of the robot, according to the mathematical model of six degrees-of-freedom manipulator which previously established and deduced kinematic equation, at first, the velocity function is added at the end of the robot arm in the MATLAB, and making the end of the robot arm reciprocate movie along the X -axis, then according to the transformation matrix of the space coordinate system, the function which is designed derivative to reference coordinate system, thereby through kinematic equations to solve each joint movement. Finally, the program is computed and simulated, after running the simulation results is imported to the txt file, which as the drive splines of the model in ADAMS.

5.3. Simulation and Analysis

Simulation and analysis of the robot arm is completed by the ADAMS and MATLAB co-simulation platform. Since the all constraints of the model were failed after import into ADAMS, it is necessary to re-add constraints to the model, the steps are as follows:

(1)Using PRO / ENGINEER Wildfire 5.0 set the x_t copy which belongs to six degrees-of-freedom manipulator model into ADAMS, and the model of robotic simulation computing platform can be obtained;

(2)The direction of gravity was settled to -Y axis of the global coordinate system in ADAMS, and the parameters were settled in units of MMKS;

(3)The Render icon was pressed to make the model into non- rendering , the center point is selected on the plane of base and Link 1 connected, and the Working Grid was established, the direction of X, Y axis were selected as the same as local coordinate system, the Joint Revolute was selected to add in the center, in order to make the Link 1 rotating about the base, the Rotational Joint Motion was selected to add in the center, as the rotation of the drive of Link 1 rotating around the base, its named is MOTION_1, adding the remaining five joints and the drive motor in the same way and named them as JOINT_3-7, MOTION_2-6;

(4)Since the base is absolutely static, so it needs to add a fixed deputy Joint Fixed, the center of the bottom of the base was fixed on the earth;

(5)Model test, after test the model has not superfluous constraint; Interactive Simulation Controls was selected, and after test the simulation model was meet the design requirements.

Then the MATLAB simulation program results which save as txt file was imported into ADAMS, spline function was inputted in six revolute joint drive motors, after running the simulation processing the Post processing was used to measure the end of the robot arm centroid velocity and displacement curves which without tension load and they are shown in Figure 3, Figure 4.

Apparent from Figure 4, in the condition of without tension the end part centric of the robot along X axis reciprocating linear motion, there is no increase in the displacement of the Y axis and Z axis; the speed at 0 of X coordinate is max, the speed is decreases to zero along the 0 point of X axis from the positive and negative direction, after the speed turn to 0 the robotic do the reverse direction.
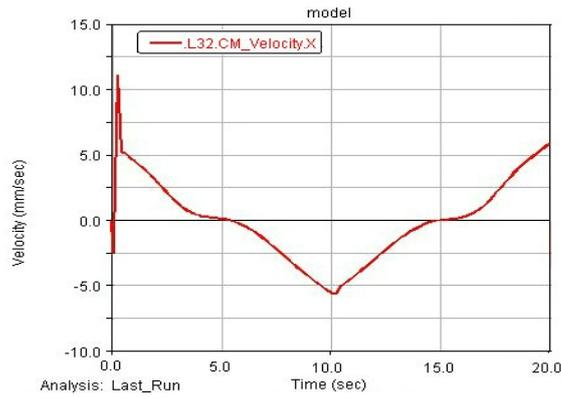
Figure 3. The End of the Robot Arm Centroid Velocity Curves
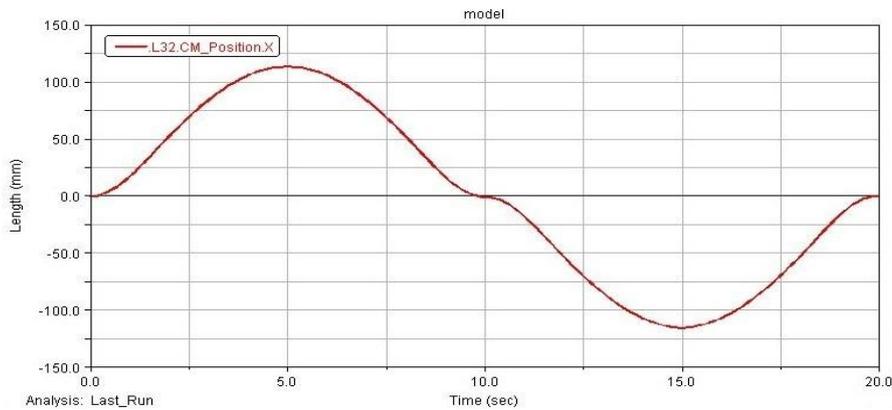
Figure 4. The End of the Robot Arm Centroid Displacement Curves without Tension Load Conditions

The arm returns to the initial position, the Applied Force icon was selected in the ADAMS, adding tension at the end of the robot arm and its size is F0, the measuring module was used to measure the angle φ which between the centric of the end and the X - axis, because of the angle which between the tension and the X-axis is same as the centric, so the size of tension along the X-axis direction is F0cosφ, along the Y-axis direction is F0sinφ, along the Z-axis direction is 0. Run the simulation again, the POST processing was used to measure the robotic arm under tension load conditions at a predetermined speed the centric of the end of arm displacement curves which is integrated along the XY axis. And the curves are shown in Figure 5.

Apparent from Figure 5, under tension load conditions, at the origin of Y-axis the centric of the end of the arm has maximum displacement increment and in the speed of the 0 position the X-axis displacement was affected by the tension component turn inward migration. Therefore, if the robot arm subjected to tension still does linear reciprocating movement along the X-axis, the inevitable consequences is in winding process the pipeline performance degradation and it is caused by the tension difference. Conversely, if the movement is along the trajectory in Figure 5, the influence of tension was reduced; thereby the performance of the pipe was improved. According to the results, we can obtain the force of the joints of the robot. Taking these force data as the compensation of the joint force, the robot can do the desired track overcoming the winding tension.
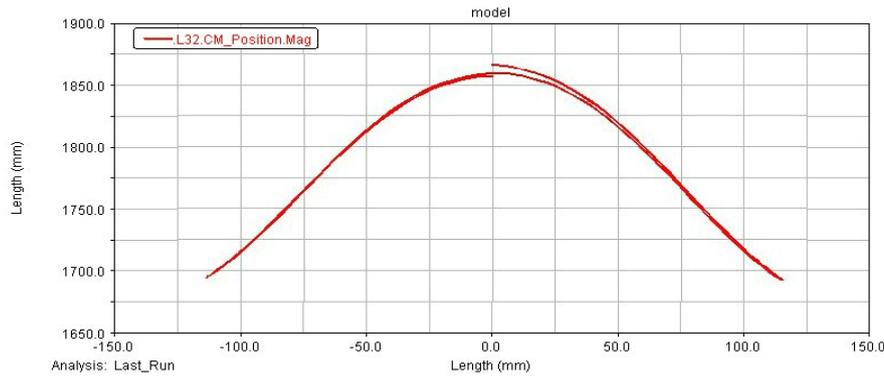
Figure 5. Under Tension Load Conditions the End of Arm Centric Displacement Curves which Integrated Along the XY Axis

6. Conclusion

In order to solve the question of the winding tracks affected by tension leading to pipeline performance degradation, we analyze the tension on the wound composite pipes and establish a winding model of robotic arm with six degrees of freedom and find the solver of the kinematic equations. We design a winding track and establish a MATLAB and ADAMS co-simulation platform. The winding track affected by the tension is simulated. According to the results, we can obtain the force of the joints of the robot. Taking these force data as the compensation of the joint force, the robot can do the desired track overcoming the winding tension.

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