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Rigid Body Kinematics Analysis Model and its Solution for Pipe Racking Device of Offshore Drilling Platform

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Abstract: With pipe racking device of offshore drilling platform as object of the research, this study builds its kinematic model on the basis of its actual motion in the pipe racking process and solves this model by the method of homogeneous coordinate transformation, then the position and posture of the PRS end effector (clamp) during the racking procedure can be achieved which is relative to the inertial reference system. The motion track and the displacement, velocity and acceleration curves of clamp are acquired by MATLAB software. The kinematic parameters of this mechanism are analyzed comparatively when the joints are in the three different motion modes: Uniform velocity, uniform acceleration-uniform deceleration and uniform acceleration-uniform velocity-uniform deceleration.

Key words: Offshore drilling platform, pipe racking device, kinematics, model, solution

INTRODUCTION

Under the trend of modernization, mechanization and automation in the international drilling industry, the automated pipe handling system for the drilling platform has been concerned by more and more domestic and international researchers (David, 1998). In this system, the PRS can do some operation on the drill-pipe stands, such as grasp, lift, drop, translation, circumgyration and so on, that is for transferring them between the wellhead and the pipe setback and it can connect the single pipe into the stand pipe with rat hole and iron roughneck (Sha *et al*., 2011).

DESCRIPTION OF PRS SIMPLIFIED MODEL

Structure of the vertical PRS is shown in Fig. 1. The stand 3 at the centre of structure droved by the top support car 1 and bottom power car 10 can slide along the up and down guide rail 2 and 9. And the stand 3 also can rotate around its own axis, thus the two robot arms can be in different directions to catch the drill-pipe stands 4 from the wellhead and put them on the pipe racking stand 7; The lifting arm 5 installed on the upper part of the stand can slide up and down along the stand by the rack and pinion interface, thus the clamp at the end of lifting arm can be driven to grasp, lift and drop the tribble and the tribble can get nearer to or farther away from the stand by a telescopic movement of the lifting arm; The righting arm 8 installed on the lower part of the stand matches the lifting arm movement to eliminate the additional vibration which is produced during the move of tribble (Cui *et al*., 2010).

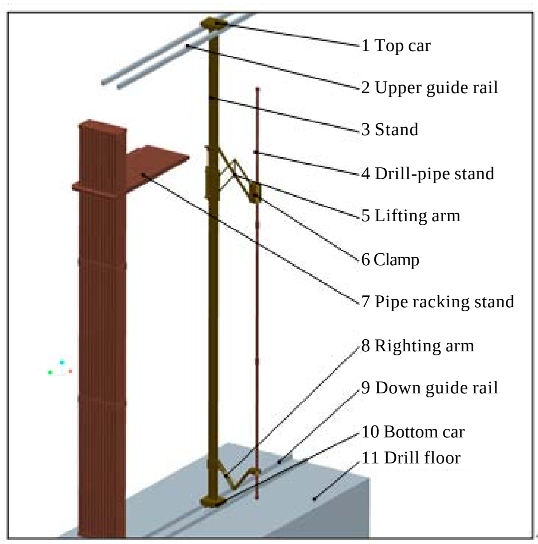

Fig. 1: Structure of the vertical PRS (Cui *et al*., 2010)

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KINEMATIC ANALYSIS OF PRS

During the pipe racking process, the righting arm moves together with the lifting arm, so it can be ignored in the kinematic analysis and course of modeling, the kinematic model of PRS is shown in Fig. 2. Link 0 is the down guide rail, link 1 is the bottom car, link 2 is the stand, link 3 is the lifting arm and link 4 is the clamp.

In the movement of the mechanism, the clamp either toward or away from the stand depends on the prismatic joint 4, the lifting arm slides up and down along the stand by the prismatic joint 3, the rotation of the stand for making the lifting arm face the wellhead or the pipe racking stand is done by the turning joint 2, the bottom car slides along the guide rail by the prismatic joint 1.

This study uses the method of homogeneous coordinate transformation for the kinematic analysis of PRS, this method combines translation with rotation to form a transformation matrix and to do the generalized coordinate change. Every simple movement of the rigid body corresponds to a simple matrix, so the multiple movements can be expressed as the product of their transformation matrixes (Han and Luo, 2010).

The coordinate system which is set up on the clamp of lifting arm is defined as a moving coordinate system C. In the beginning, the position and posture of the moving coordinate system C which is relative to the inertial reference system S, is:

$$C = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & b_0 \\ 0 & 0 & 1 & c_0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

In the movement of PRS, the clamp grasping the tribble and performing the racking operation is accomplished by the four joints working together, that is the clamp can reach the anticipated position through a series of transformation. Set the transformation matrix to T and the joint variables to a, θ, c and b, respectively. The rotational transformation of joint 2 is relative to the moving coordinate system which is described by the translational transformation of joint 1, the translational transformation of joint 3 is relative to the moving coordinate system which is described by the rotational transformation of joint 2, the translational transformation of joint 4 is relative to the moving coordinate system which is described by the translational transformation of joint 3. Generally, if post-multiplying a transformation matrix of coordinate system by another translational and (or) rotational transformation matrix, the second transformation is relative to the moving coordinate system

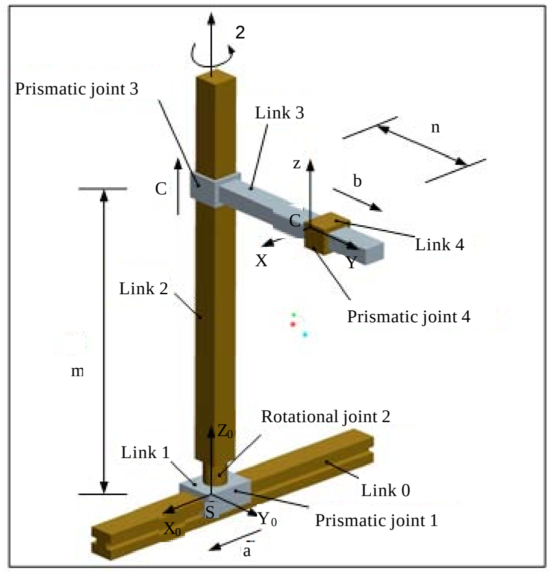

Fig. 2 Kinematic Model of the PRS (Yao, 2012)

which is described by the first transformation; if premultiplying the coordinate system matrix by a translational and (or) rotational transformation matrix, the transformation is relative to the inertial reference system (the fixed coordinates system) (Chen and Wang, 1995). With the description above, the transformation matrix T is:

$$T = \mathrm{Trans}(a,0,0)\cdot \mathrm{Rot}(z,\theta)\cdot \mathrm{Trans}(0,0,c)\cdot \mathrm{Trans}(0,b,0)$$

After the transformation T which is relative to the inertial reference system, the moving coordinate system C become X, that means the position and posture of the clamp become:

$$X = TC = \begin{bmatrix} 1 & 0 & 0 & a \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}\begin{bmatrix} \cos\theta & -\sin\theta & 0 & 0 \\ \sin\theta & \cos\theta & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & c \\ 0 & 0 & 0 & 1 \end{bmatrix}$$
$$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & b \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & b_0 \\ 0 & 0 & 1 & c_0 \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta & 0 & -(b+b_0)\sin\theta + a \\ \sin\theta & \cos\theta & 0 & (b+b_0)\cos\theta \\ 0 & 0 & 1 & c+c_0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

During the actual pipe racking process, a motion period of the PRS can be divided into seven stages: first, the arm is stretched out (joint 4 acting), then the drill-pipe stand is grabbed by the gripper; second, the arm is risen (joint 3 acting), the tribble is lifted vertically; third, the arm is retracted, the stand is rotated 180 degrees while the bottom car is moving along the rail (joint 1,2,4 acting together at the third stage), this series of actions are performed at the same time to transfer the drill-pipe stand from the wellhead to the pipe racking stand; forth, the arm is stretched out (joint 4 acting), the tribble is moved to the specified location on the pipe racking stand; fifth, the arm is fell down to lower the tribble and touch the drill floor; sixth, the arm is retracted (joint 4 acting) which can avoid the motion interference between the arm and pipe racking stand; seventh, the stand is rotated 180 degrees, at the same time, the bottom car is moving back along the rail (joint 1, 2 acting together), the mechanism returns to the initial state. According to the above analysis result, the movement path of the clamp (link 4) in a motion cycle can be simulated by MATLAB software which is shown in Fig. 3.

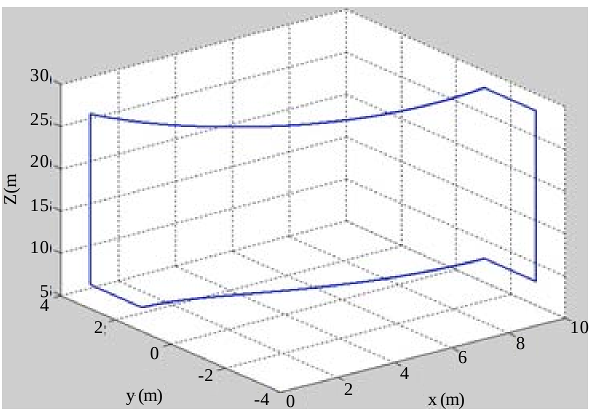

Fig. 3: Movement path of the clamp

DISPLACEMENT, VELOCITY, ACCELERATION ANALYSIS OF CLAMP IN PRS

Assuming the joint variables to be a, θ, c and b, respectively, C_i is the mass center of link I, v_{C_i} is the velocity of C_i, $\dot{v}_{C_i}$ is the acceleration. The following is the velocity and acceleration of the link 4 (the clamp).

According to:

$$\begin{cases} x_{C_4} = a - (b + b_0)\cdot \sin\theta \\ y_{C_4} = (b + b_0)\cdot \cos\theta \\ z_{C_4} = c + c_0 \end{cases}$$

it follows:

$$v_{C_4} = \begin{bmatrix} \dot{a} - \dot{b}\cdot \sin\theta - b_0\cdot\dot{\theta}\cdot\cos\theta - b\cdot\dot{\theta}\cdot\cos\theta \\ \dot{b}\cdot\cos\theta - b_0\cdot\dot{\theta}\cdot\sin\theta - b\cdot\dot{\theta}\cdot\sin\theta \\ \dot{c} \end{bmatrix}$$

$$\dot{v}_{C_4} = \begin{bmatrix} \ddot{a} - (\ddot{b}\cdot\sin\theta + \dot{\theta}\,\dot{b}\cdot\cos\theta) - (b_0\cdot\ddot{\theta}\cdot\cos\theta - b_0\cdot\dot{\theta}^2\cdot\sin\theta) - (\dot{\theta}\,\dot{b}\cdot\cos\theta + b\cdot\ddot{\theta}\cdot\cos\theta - b\cdot\dot{\theta}^2\cdot\sin\theta) \\ (\ddot{b}\cdot\cos\theta - \dot{\theta}\cdot\dot{b}\cdot\sin\theta) - (b_0\cdot\ddot{\theta}\cdot\sin\theta + b_0\cdot\dot{\theta}^2\cdot\cos\theta) - (\dot{\theta}\cdot\dot{b}\cdot\sin\theta + b\cdot\ddot{\theta}\cdot\sin\theta + b\cdot\dot{\theta}^2\cdot\cos\theta) \\ \ddot{c} \end{bmatrix}$$

On the basis of the analysis above and considering the movement of PRS in the actual automated racking process, when each joint moves in the three ways: Uniform speed, uniform acceleration-uniform deceleration and uniform acceleration-uniform speed-uniform

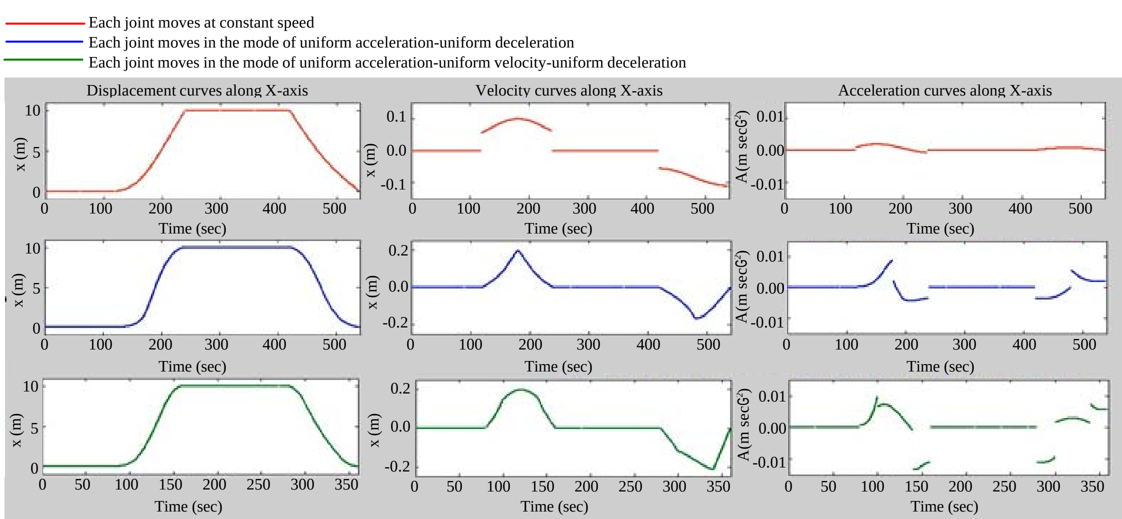

Fig. 4: Displacement, velocity and acceleration curves along X-axis

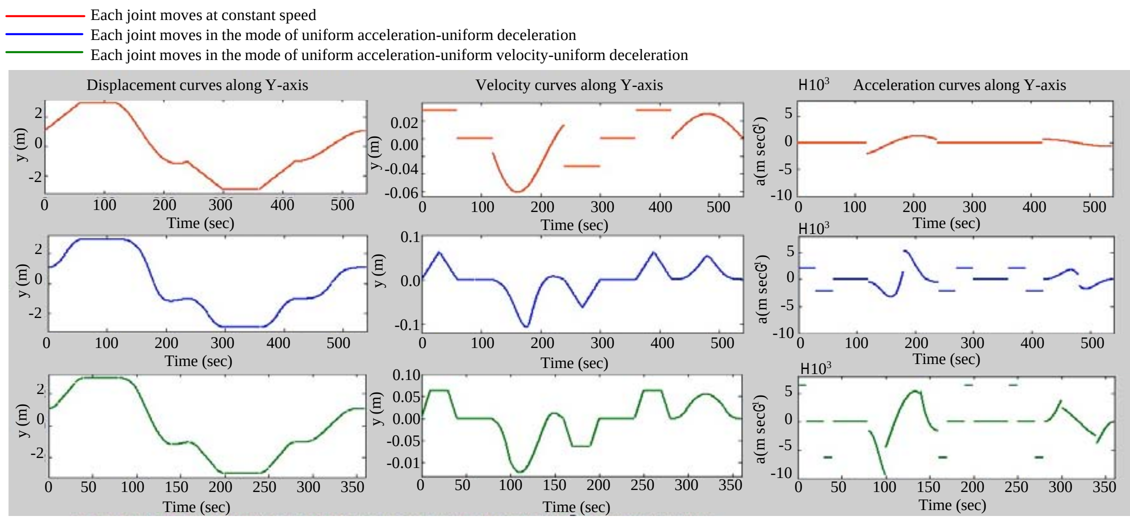

Fig. 5: Displacement, velocity and acceleration curves along Y-axis

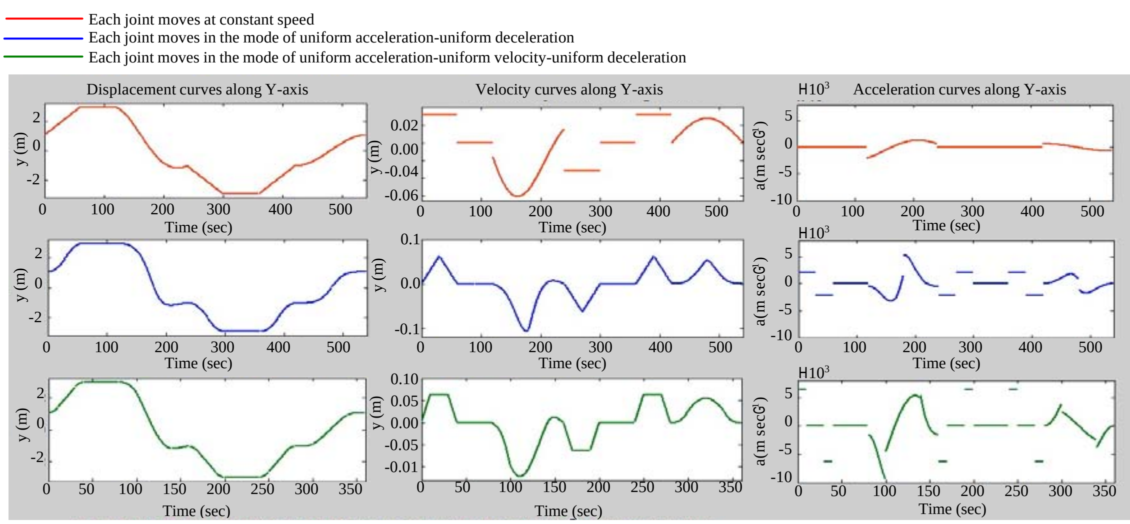

Fig. 6: Displacement, velocity and acceleration curves along Z-axis

deceleration, the displacement, velocity and acceleration curves of the clamp along X-axis, Y-axis and Z-axis can be obtained by MATLAB (shown as the Fig. 4-6).

Based on the kinematical parameter figures above, if each joint of the PRS moves at constant speed, the velocities of the joints would reach their respective specified magnitudes at the beginning of the motion, so there are sudden-changes of the velocities and at the moment, the accelerations go to infinity which would form sizeable inertia force for the mechanism, therefore, in the actual joints motion control, this mode is not recommended; if each joint of the PRS moves in the mode of uniform acceleration-uniform deceleration, compared with the first mode, the motion is more gentle and the accelerations are smaller, that means it would not produce sizeable inertia force in this mode; if each joint of the PRS moves in the mode of uniform acceleration-uniform speed-uniform deceleration, the motion is gentle, the accelerations and inertia force are also small, but in comparison with the second mode, this mode spends less time and has higher efficiency. Through the above comparatively analysis, the mode of uniform acceleration-uniform speed-uniform deceleration should be adopted in the joints motion control.

CONCLUSION

In this study, the method of homogeneous coordinate transformation is employed to solve the rigid body kinematic model of PRS and then the kinematic characteristics of the mechanism end effector (clamp) can be obtained. When each joint moves in the three different motion modes: Uniform velocity, uniform acceleration-uniform deceleration, uniform acceleration-uniform velocity-uniform deceleration, according to the comparatively analysis of displacement, velocity and acceleration of the clamp, the following conclusions are made: If each joint of the PRS moves at constant speed, there would be sizeable inertia force in the mechanism. By contrast, applying the mode of uniform acceleration-uniform velocity-uniform deceleration can not only reduce hours and increase efficiency, but also not cause great inertia force.

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