Journal of Applied Sciences

ISSN 1812-5654

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Journal of Applied Sciences 13 (22): 5287-5297, 2013
ISSN 1812-5654 / DOI: 10.3923/jas.2013.5287.5297

Kinematic and Dynamic Analysis of Clamping Manipulator for Drill Pipe Racking System

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Abstract: The clamping manipulator of automatic drill pipes racking system of offshore drilling platform was designed in this dissertation. This kind of manipulator totally meets the design requirements of lightness, large load, extensive service, simple and reliable structure and high efficient, etc, Comparing with other clamping manipulator of drill pipe racking systems, each sub manipulator equipped with just only one drive part can exactly meet the work demands, as greatly simplifies the mechanical structure and improves the working reliability. In this dissertation, the kinematical equation of manipulator by using the closed vector graph method was built , the kinematics simulation was realized based on ADAMS software and the result has verified the validity of the manipulator design. By comparison of the dynamics equation of manipulator by the method of traditional equivalent mechanical model and the dynamics simulation based on ADAMS software, Some variable curves of mechanical components of manipulator, which were closer to reality, were got for the convenience of the design of control system later.

Key words: Pipe racking, clamping manipulator, kinematics simulation, dynamics simulation

INTRODUCTION

The automation of drill pipe racking system is an important link of realizing the automation of offshore drilling platform (Liu *et al*., 2007). Drill pipe racking system was mainly used for the manipulating process from the wellhead to pipe setback in the whole drilling process. Clamping manipulator is installed in the main arm of drill pipe racking system and coordinates with the guide clamp to realize clamping for varies drills (such as drill pipes, setback, drill collar, riser and casing etc. We replace drills by pipelines because the drills are all tubular) in working process (Ward *et al*., 1976). Clamping manipulator has great force in clamping (Jiang *et al*., 2008), which can assure the accuracy of location not to slip between itself and the pipeline in working process (Rohde *et al*., 2010). Clamping manipulator has large force and velocity in the process of grabbing and releasing for the demand of short time in manipulating. It is essential to carry out kinematics and dynamic analysis for clamping manipulator. In Land drill rig mast automatic Drainage System (Zhang *et al*., 2011), it mainly introduced the components and working process of drill pipe racking system without analyzing the specific structure of it.

In Design for Column Pipe Racking Device of Offshore Drilling Platform (Cui *et al*., 2010), the designed clamping part of drill pipe racking system has the big difference from the structure in this study and there was no further analysis for the working of manipulator. Different from mainly analyzing the clamping manipulator in this study, In The design of the pipe racking system for land rig (Tong *et al*., 2011) and Land drill rig mast automatic Drainage System, it mainly researched the components of structure, realization of function and parameter of technique of drill pipe racking system, without illustrating specific analysis for every structure. In Driving Device Project Designing of Offshore Rig Pipe Racking System (Li *et al*., 2011), the spatial layout and the selection of driven system were analyzed and were quite different from the kinematics and dynamic analysis carried out in this study. This study introduced the specific structure and working principle of the clamping manipulator. The kinematics and dynamics models of manipulator were built by using the vector analysis method and the equivalent mechanical model method. The kinematics and dynamics simulation of the clamping manipulator was realized based on the ADAMS software.

CLAMPING MANIPULATOR

The clamping manipulator of drill pipe racking system consists of three groups of manipulators, which are respectively driven by three hydraulic cylinders that coordinate to accomplish the task of clamping pipeline by the order of work scheduled. Each drive mechanism is designed in dependent to avoid the mutual coupling

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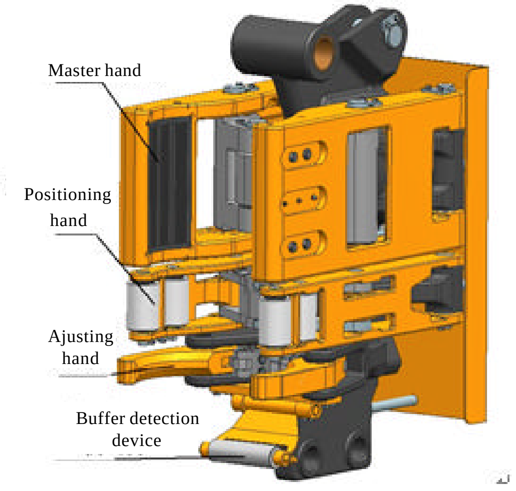

Fig. 1: Clamping manipulator structure

among sub systems so that it has strong adaptability, stability and reliability and belongs to the automatic centering mechanism. Three-dimensional structure of manipulator is shown in Fig. 1.

In Fig. 1, a clamping manipulator is mainly composed of master hand, positioning hand, adjusting hand and buffer detection device, of which the first three ones are the main clamping parts of manipulator.

Buffer detection device is used to protect the main clamping component of manipulator from be impacted by pipelines through detecting the position of pipeline relative to the manipulator and sending the work instruction for the control system in the working process. In the working process of clamping the pipe, adjusting hand contacting with pipeline at first adjusts the position of pipeline, which can restrict large-scale shaking of pipelines to assure the reliability of positioning hand. After that, positioning hand realizes line contact with pipeline by four rollers front-end and automatic centering of pipeline by the rolling of contact rollers. At last, master hand clamps the pipeline through the front-end V-shaped block designed and generates the enough large friction force under the action of drive hydraulic cylinder. So that the pipeline can keep stability in the process of the discharge.

KINEMATICS ANALYSIS

Clamping manipulator of drill pipe racking system needs to provide a large clamping force for pipeline and has a complex work flow process of clamping pipeline. Hence it is necessary to carry out kinematic analysis for each part of that.

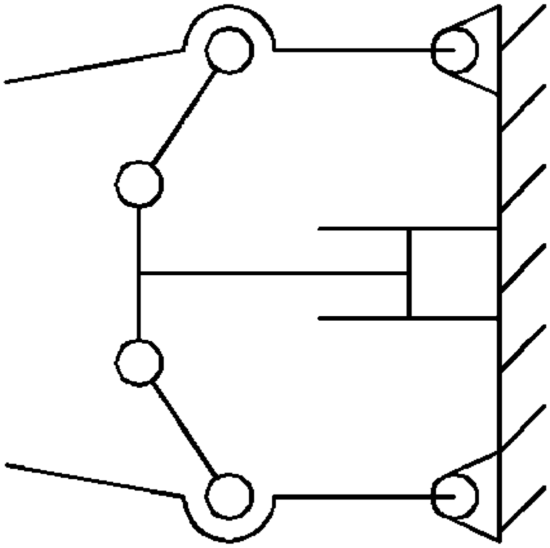

Fig. 2: Mechanical diagram of master hand and positioning hand

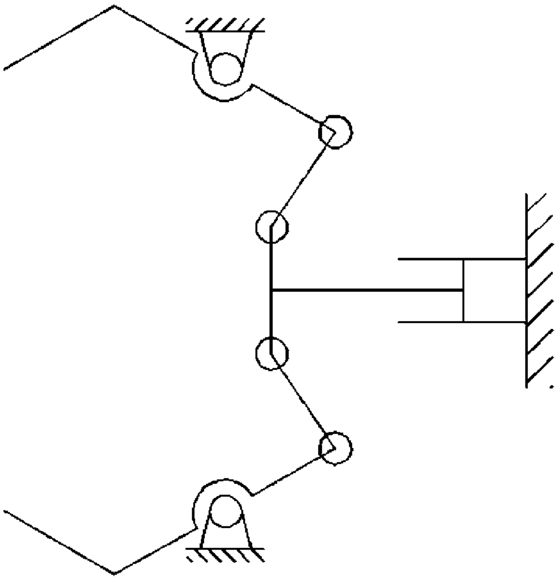

Fig. 3: Adjusting hand mechanical diagram

Establishment of mathematical model: The work principles of master hand and positioning hand are same and its mechanical diagram is shown in Fig. 2. Mechanical diagram of adjusting hand is shown in Fig. 3. We could extract the single manipulator as simplified motion diagram as shown in Fig. 4 and 5, as the driving components of each part are all hydraulic cylinders and the moving parts are symmetrical.

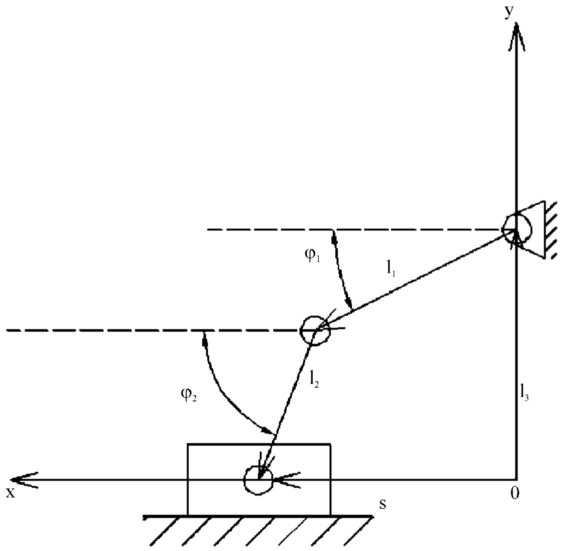

Fig. 4: Kinematical diagram of master hand and positioning hand

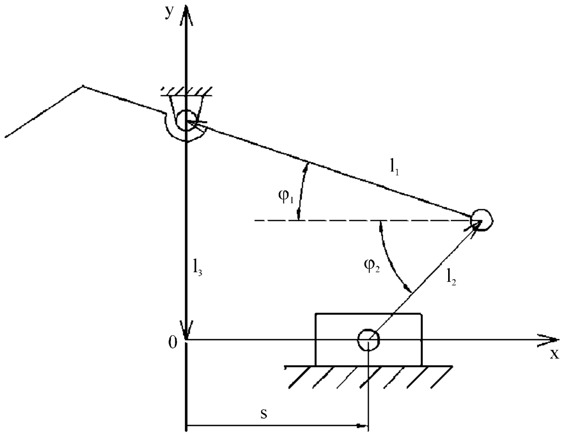

Fig. 5: Adjusting hand kinematical graph

Displacement analysis: In Fig. 4, we obtain that for the master hand and positioning hand, each rod forms a closed graphics with O as the origin point and the following vector equation is obtained:

$$\vec{l}_1+\vec{l}_2+\vec{l}_3=\vec{s} \tag{1}$$

According to the projection of each vector in X and Y axis, the following equations are obtained:

$$\begin{cases} l_1\cos\varphi_1+l_2\cos\varphi_2=s \\ l_1\sin\varphi_1+l_2\sin\varphi_2=l_3 \end{cases} \tag{2}$$

In Figure 5 we obtain that for the adjusting hand, each rod also forms a closed graphics with O as the origin point and the following vector equation is obtained:

$$\vec{l}_1+\vec{l}_3=\vec{s}+\vec{l}_2 \tag{3}$$

According to the projection of each vector in X and Y axis, the following vector equations are obtained:

$$\begin{cases} l_1\cos\varphi_1=s+l_2\cos\varphi_2 \\ l_3-l_1\sin\varphi_1=l_2\sin\varphi_2 \end{cases} \tag{4}$$

Velocity analysis: Differentiating Eq. 2 and 3 with respect to time, we obtain the angular velocity set of equations of each link.

Velocity equations set of master hand and positioning hand is as follows:

$$\begin{cases} -l_1\sin\varphi_1\cdot\dot{\varphi}_1-l_2\sin\varphi_2\cdot\dot{\varphi}_2=\dot{s} \\ l_1\cos\varphi_1\cdot\dot{\varphi}_1+l_2\cos\varphi_2\cdot\dot{\varphi}_2=0 \end{cases} \tag{5}$$

Velocity set equations of adjusting hand is as follows:

$$\begin{cases} -l_1\sin\varphi_1\cdot\dot{\varphi}_1=-l_2\sin\varphi_2\cdot\dot{\varphi}_2+\dot{s} \\ -l_1\cos\varphi_1\cdot\dot{\varphi}_1=l_2\cos\varphi_2\cdot\dot{\varphi}_2 \end{cases} \tag{6}$$

Acceleration analysis: Differentiating Eq. 5 and 6 with respect to time, angular acceleration appears in the equation. Then we obtain the angular acceleration set of equations.

Angular acceleration equation sets of master hand and positioning hand are as follows:

$$\begin{cases} -l_1(\cos\varphi_1\cdot\dot{\varphi}_1{}^2+\sin\varphi_1\cdot\ddot{\varphi}_1) \\ -l_2(\cos\varphi_2\cdot\dot{\varphi}_2^2+\sin\varphi_2\cdot\ddot{\varphi}_2)=\ddot{s} \\ l_1(-\sin\varphi_1\cdot\dot{\varphi}_1{}^2+\cos\varphi_1\cdot\ddot{\varphi}_1) \\ +l_2(-\sin\varphi_2\cdot\dot{\varphi}_2^2+\cos\varphi_2\cdot\ddot{\varphi}_2)=0 \end{cases} \tag{7}$$

$$\begin{cases} -l_1(\cos\varphi_1\cdot\dot{\varphi}_1{}^2+\sin\varphi_1\cdot\ddot{\varphi}_1)= \\ -l_2(\cos\varphi_2\cdot\dot{\varphi}_2^2+\sin\varphi_2\cdot\ddot{\varphi}_2)+\ddot{s} \\ -l_1(-\sin\varphi_1\cdot\dot{\varphi}_1{}^2+\cos\varphi_1\cdot\ddot{\varphi}_1)= \\ l_2(-\sin\varphi_2\cdot\dot{\varphi}_2^2+\cos\varphi_2\cdot\ddot{\varphi}_2) \end{cases} \tag{8}$$

All the above equation sets exist three unknown variables, namely φ_1, φ_2 and s. When one variable is endowed an arbitrary value, the relationship among other variables can be determined by calculating.

Kinematics simulation: Because it can support a variety of graphical format for ADAMS/View software, this manipulator built the entity model by UG, entity model should be imported into ADAMS software after it is converted to Parasolid format, then codes bars and distinguishes color of every part. The imported model is shown in the Fig. 6.

Because the master hand, positioning hand and adjusting hand of manipulator are all made of steel, so all materials of this simulation will be set consistently, the position of mass center of each rod should be preset. The restraint of piston rod is the slide pair, others are the rotation pair between rods or between rod and manipulator. Meanwhile, the driving components of three claws of manipulator are piston rod of hydraulic cylinder. The velocity and motion time are set according to the actual requirement. Specific parameters are shown in Table 1.

After setting the motion time, we simulate according to the time of master hand that is 6 sec. After simulation, the laws of motion of every rod can be measured and motion relationship of rod also can be measured directly.

Table 1: Piston moving parameters

Parameter	Master hand piston rod	Positioning hand piston rod	Adjusting hand piston rod
Extend speed (mm sec^{-1})	13.00	80.00	63.00
Extend time (sec)	3.20	0.50	0.95
Retract speed (mm sec^{-1})	16.30	133.00	113.00
Retract time (s)	2.55	0.28	0.53

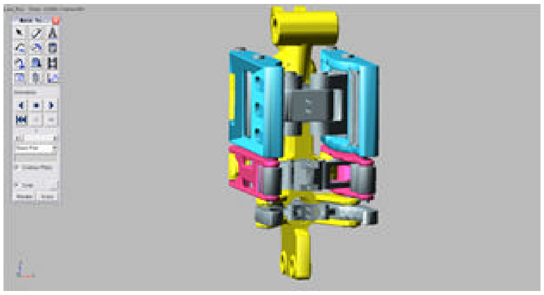

Fig. 6: ADAMS model of manipulator

Simulation Analysis of master hand: The driving link of master hand is piston rod. Its law of motion is shown in Fig. 7. From the figure, we know that the initial velocity of piston rod is 13 mm sec^{-1} along Y negative axis. The value of displacement of piston rod will reach maximum after 3 sec, then piston rod moves backward until back to the initial position. The result verifies the validity of the drive.

Only one claw of master hand needs to be measured, because it is symmetric. As shown in Fig. 8, the velocity and acceleration of master hand are relatively stable under the same direction. In the different states whether the piston rod extends or retracts, the change tendencies of acceleration are same.

Simulation analysis of positioning hand: The movement of positioning hand should finish before the master hand and confirm the position of drilling pipe for convenience of the work of master hand. The driving link is the piston rod of positioning hand. Its law of motion is shown in Fig. 9. With the change of the movement direction of the piston rod, the displacement also changes constantly until back to initial position.

As shown in the Fig. 10, the angular velocity and angular acceleration of positioning hand are in the same change. Positioning hand moves stably and produces the different angular acceleration with the movement of piston rod. Meanwhile, the change tendency in opposite process is generally consistent.

Simulation analysis of adjusting hand: Adjusting hand plays a supplementary role in the whole working process of manipulator, so its work time is between the work

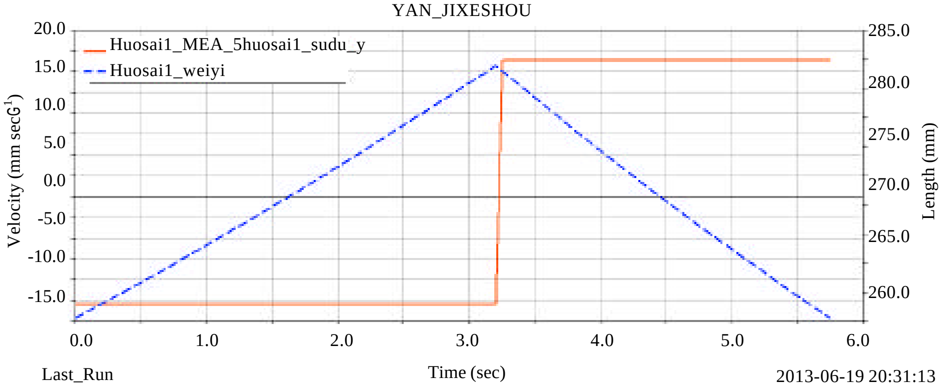

Fig. 7: Simulation curves of master hand piston, Displacement-velocity

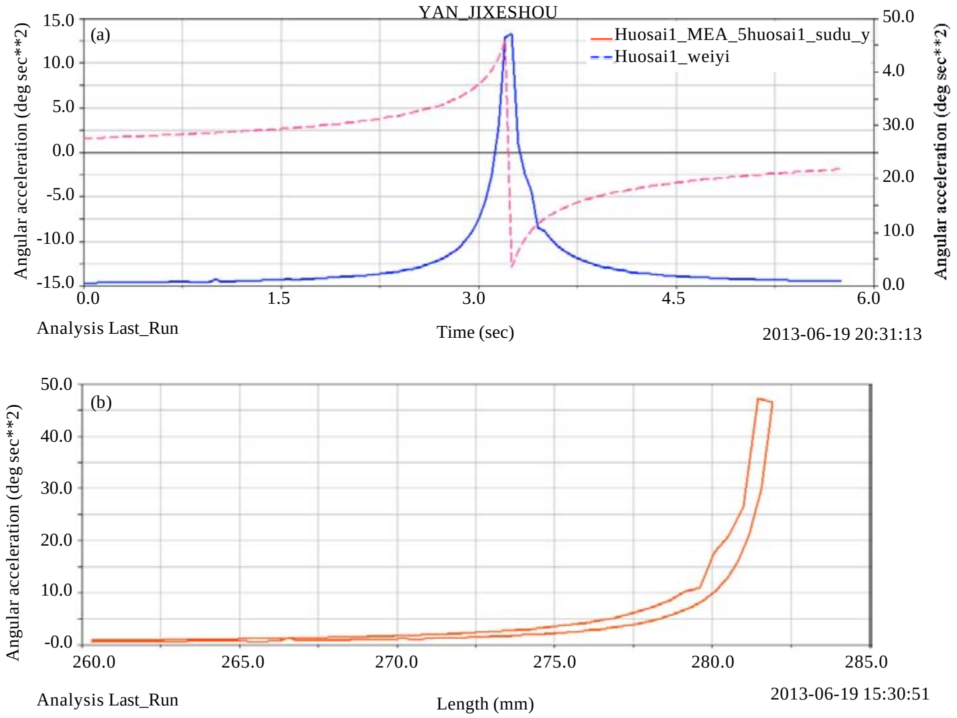

Fig. 8(a-b): Master hand simulation curves Angular velocity; Angular acceleration (a) Angular velocity and angular acceleration of master hand (b) Angular acceleration in different displacement

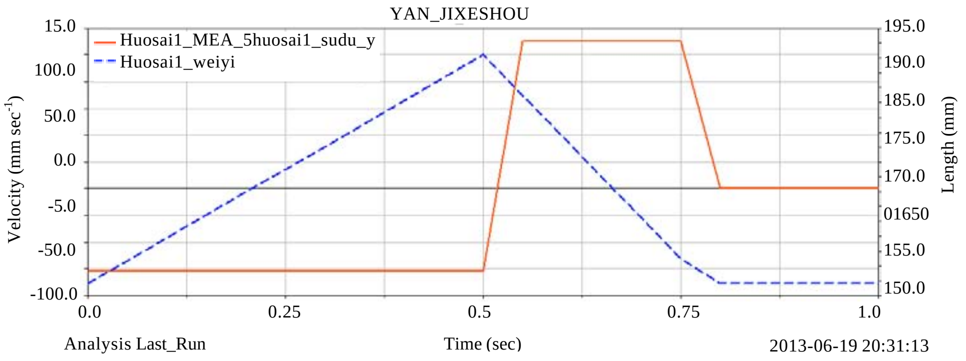

Fig. 9: Piston simulation curves of positioning hand, Angular velocity and angular acceleration of positioning

times of master hand and positioning hand. In the process of simulation analysis, the curve in Figure 11 is the motion law of piston rod of adjusting hand. Like the other two parts, the displacement and velocity of piston rod are in direct proportion. Finally, it finishes a cyclic action and then gets back to the initial position.

Because the movement of adjusting hand should be faster than the other two manipulators at the loosen moment, so the retraction speed of piston rod will be faster. As shown in the Fig. 12, the acceleration and velocity of adjusting hand in return process are significantly higher than in the clamping process. This is coincided with the design requirement.

KINETIC ANALYSIS

All the parts of clamping manipulator are hydraulic driving whose constant thrust and tension are supported by hydraulic cylinder. Resistance appeares when manipulator clamped target pipe, so kinetic analysis is required.

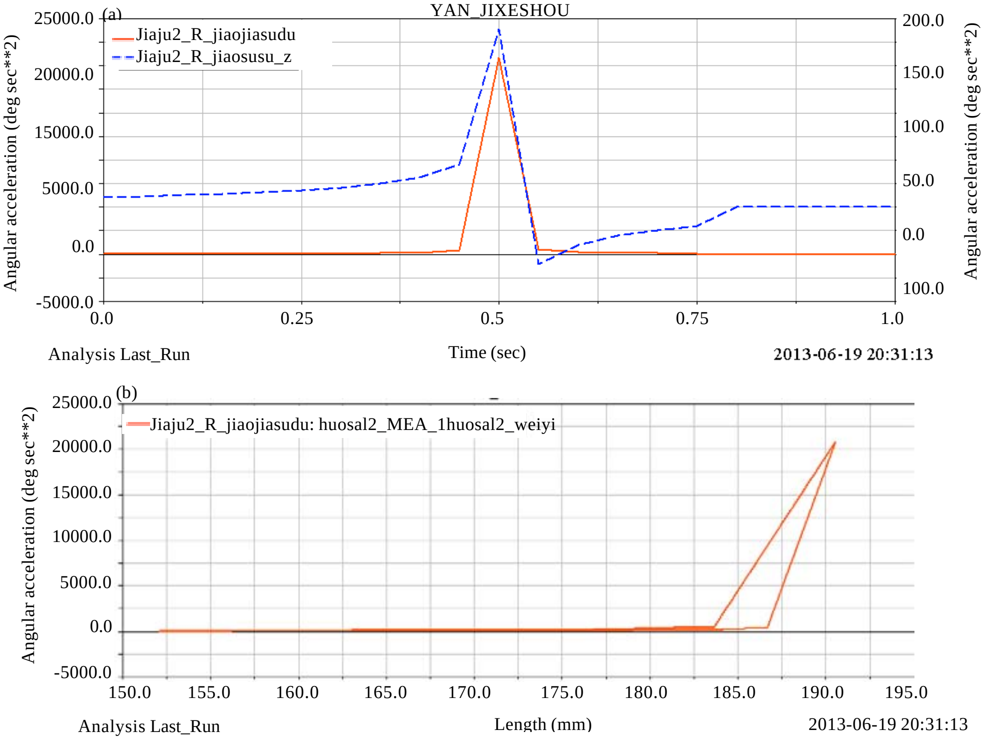

Fig. 10(a-b): Positioning hand simulation curves (a) Angular velocity and angular acceleration of positioning hand and (b) Angular acceleration in different displacement

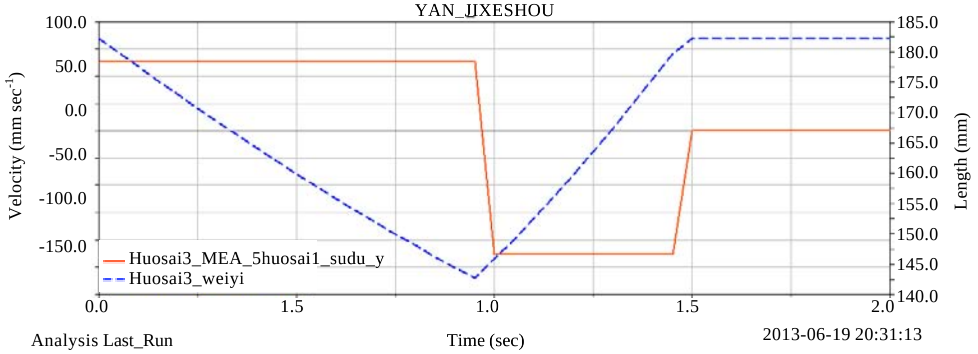

Fig. 11: Adjusting hand piston simulation curves

Mathematical modeling: Although, three parts of clamping manipulator have a little difference, all of them are formed by five connecting rod and a frame and the way of action of driving force and resisting moment are exactly same. So analysis process is same. Master hand and positioning hand are taken for example in this study. As shown in Fig. 13, it is the simplified diagram of unilateral model of manipulator. While the hydraulic cylinder piston rod can be viewed as the slider and F is the driving force whose value is taken half of the actual force. M is resisting moment, the weight of piston rod is m3, the rotational inertia of the mechanical arm is J_1 while the weight of link 2 is not taken into account.

Because the manipulator has only one degree of freedom, so we can use the method of equivalent mechanical model for analysis, namely the increment of work make by the force is equal to the increment of kinetic energy of system. Mechanical arm is as the equivalent object:

$$M_v = -M + F\frac{\dot{s}}{\dot{\varphi}_1} \tag{9}$$

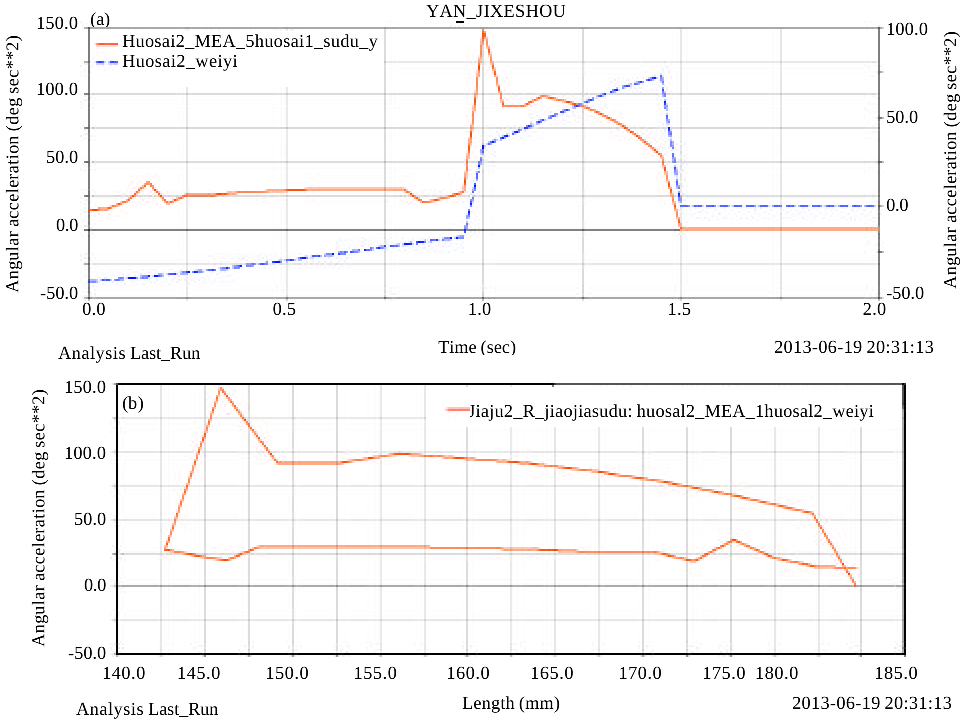

Fig. 12(a-b): Adjusting hand simulation curves, (a) Angular velocity and angular acceleration of adjusting hand and (b) Angular acceleration in different displacement

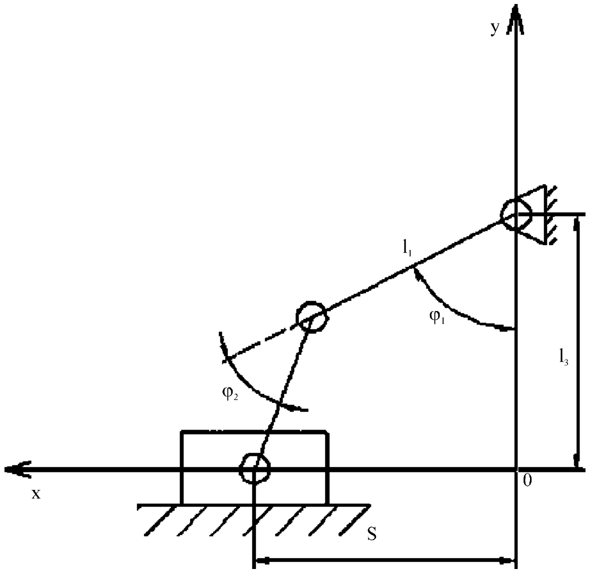

Fig. 13: Master hand and positioning hand kinetic diagram

$$J_v = J_1 + m_3\left(\frac{\dot{s}}{\dot{\varphi}_1}\right)^2 \tag{10}$$

$$M_v = J_v\ddot{\varphi}_1 + 0.5\dot{\varphi}_1^2\frac{dJ_v}{d\varphi_1} \tag{11}$$

The following equation set is obtained from the geometric relationship as shown in the figure.

$$\begin{cases} l_3 = l_1\cos\varphi_1 + l_2\cos(\varphi_1 - \varphi_2) \\ s = l_1\sin\varphi_1 + l_2\sin(\varphi_1 - \varphi_2) \end{cases} \tag{12}$$

From the equation set we can get the following equation:

$$s = l_1\sin\varphi_1 + l_2\sin\left(\arccos\left[\frac{l_3 - l_1\cos\varphi_1}{l_2}\right]\right) \tag{13}$$

Differentiating Eq. 12 with respect to time, we can obtain:

$$\frac{\dot{s}}{\dot{\varphi}_1} = l_1\cos\varphi_1 - \frac{(l_3 - l_1\cos\varphi_1)l_1\sin\varphi_1}{\sqrt{l_2^2 - (l_3 - l_1\cos\varphi_1)^2}} \tag{14}$$

So we put Eq. 9, 10, 14 into the Eq. 11, then calculate the kinetic equation of master hand and positioning hand:

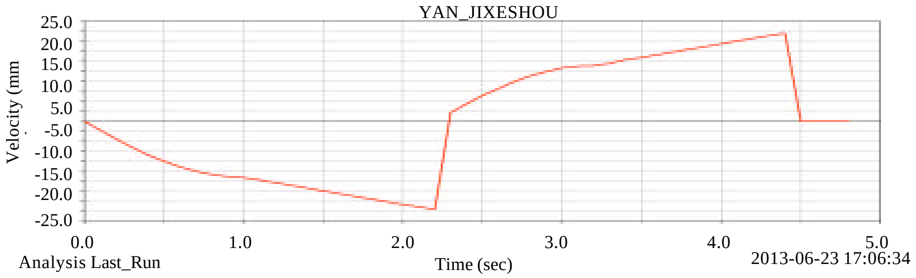

Fig. 14: Piston speed trend curve

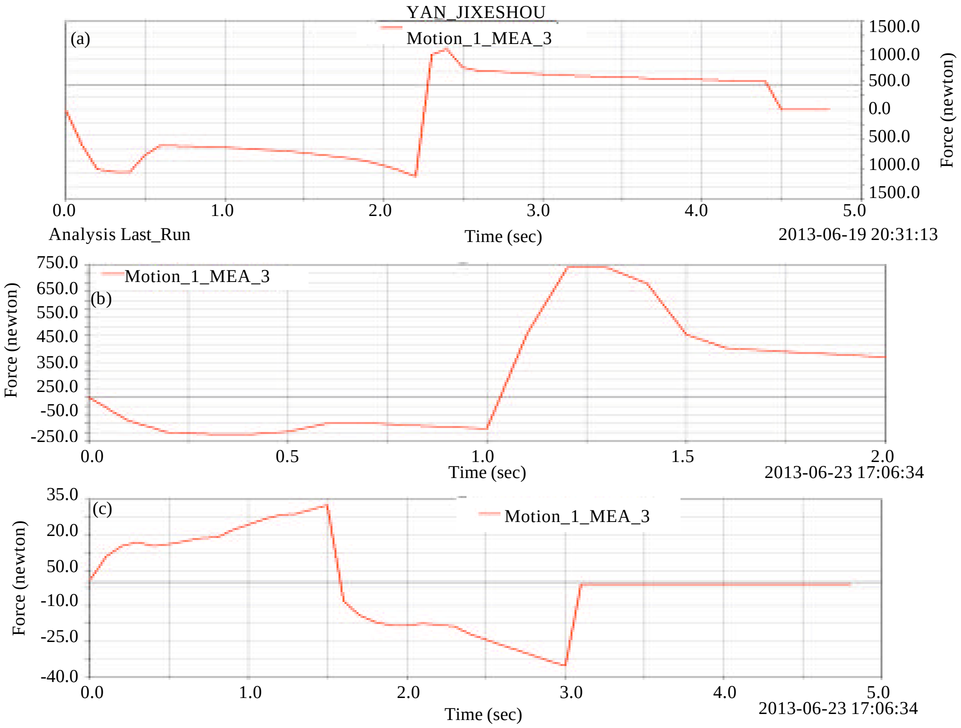

Fig. 15(a-c): Robot driving force curve, (a) Master hand, (b) Positioning hand and (c) Adjusting hand

$$
\begin{aligned}
&-M+F(l_1\cos\varphi_1-\frac{(l_3-l_1\cos\varphi_1)l_1\sin\varphi_1}{\sqrt{l_2^2-(l_3-l_1\cos\varphi_1)^2}})=\\
&[J_1+m_3(l_1\cos\varphi_1-\frac{(l_3-l_1\cos\varphi_1)l_1\sin\varphi_1}{\sqrt{l_2^2-(l_3-l_1\cos\varphi_1)^2}})^2]\ddot{\varphi}_1\\
&+m_3\dot{\varphi}_1^2[l_1\cos\varphi_1-\frac{(l_3-l_1\cos\varphi_1)l_1\sin\varphi_1}{\sqrt{l_2^2-(l_3-l_1\cos\varphi_1)^2}}]\\
&[-l_1\sin\varphi_1-\frac{l_1{}^2\sin^2\varphi_1-(l_3-l_1\cos\varphi_1)l_1\cos\varphi_1}{\sqrt{l_2^2-(l_3-l_1\cos\varphi_1)^2}}\\
&-\frac{(l_3-l_1\cos\varphi_1)^2 l_1{}^2\sin^2\varphi_1}{\sqrt[3]{l_2^2-(l_3-l_1\cos\varphi_1)^2}}]
\end{aligned}
$$

Kinetics simulation

Simulation analysis without pipe contacting: ADAMS model is constrained according to known condition. The quality of each rod and moment of inertia are preset. The coefficient of friction is added on all joints while static coefficient is set as 0.5 and dynamic coefficient is set as 0.3. The driving force is imposed in order to make the piston move with the velocity as shown at the Fig. 14.

The relationship between angular velocity, angular acceleration, displacement of center of mass and constraint counter-force of the joints could be got through the measurement after simulation. Driving force of each manipulator is shown in the Fig. 15. The curves of angular velocity and angular acceleration of each manipulator are shown in the Fig. 16. The constraint counter-force is shown in the Fig. 17.

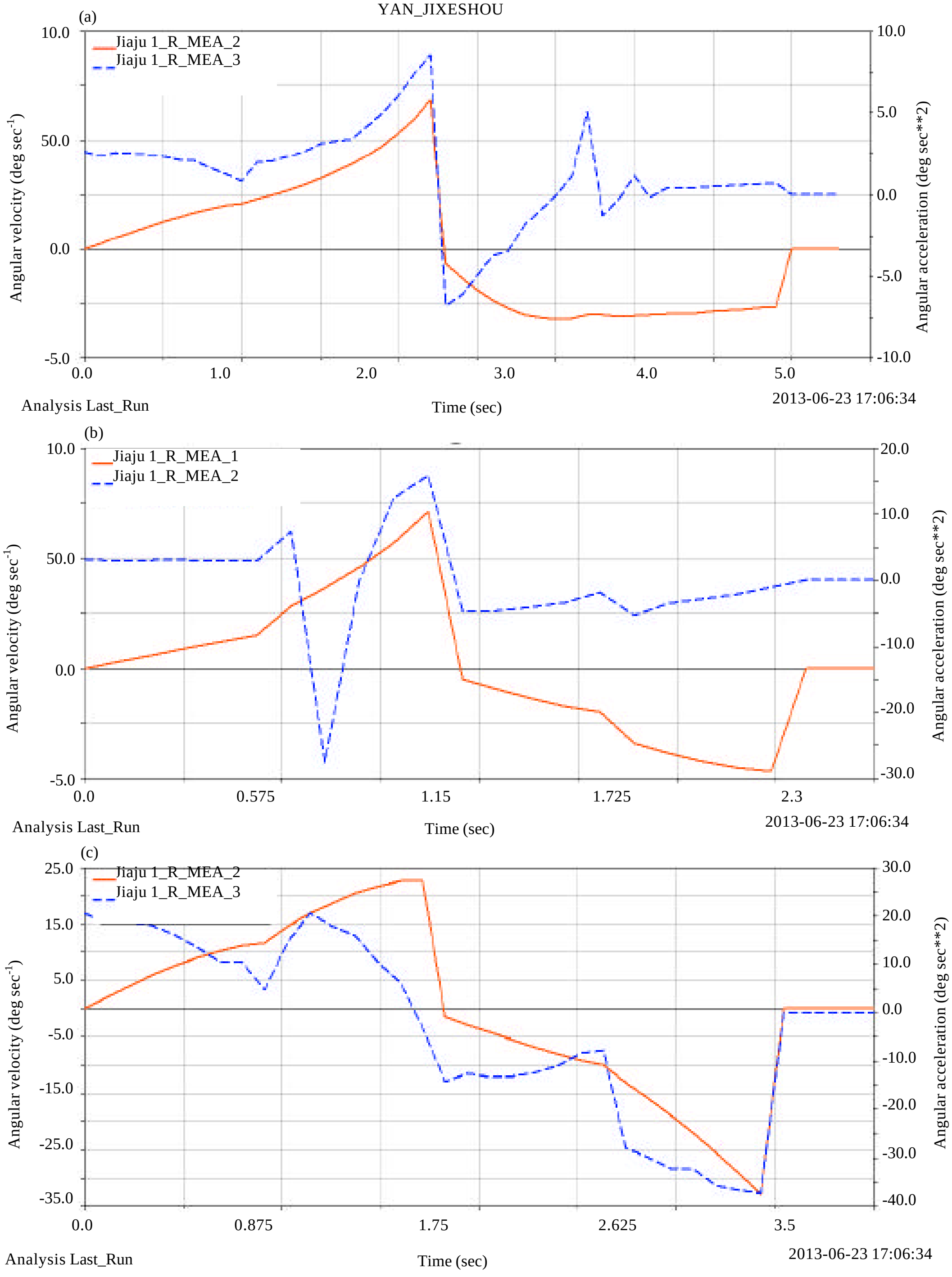

Fig. 16(a-c): Angular velocity and angular acceleration curves (a) Master hand, (b) Positioning hand and (c) Adjusting hand

It can be seen that compared with the classical calculation method, the curve produced by ADAMS simulation fluctuates greatly due to the more actual constraints, not completely equivalent of components and the different methods of calculation.

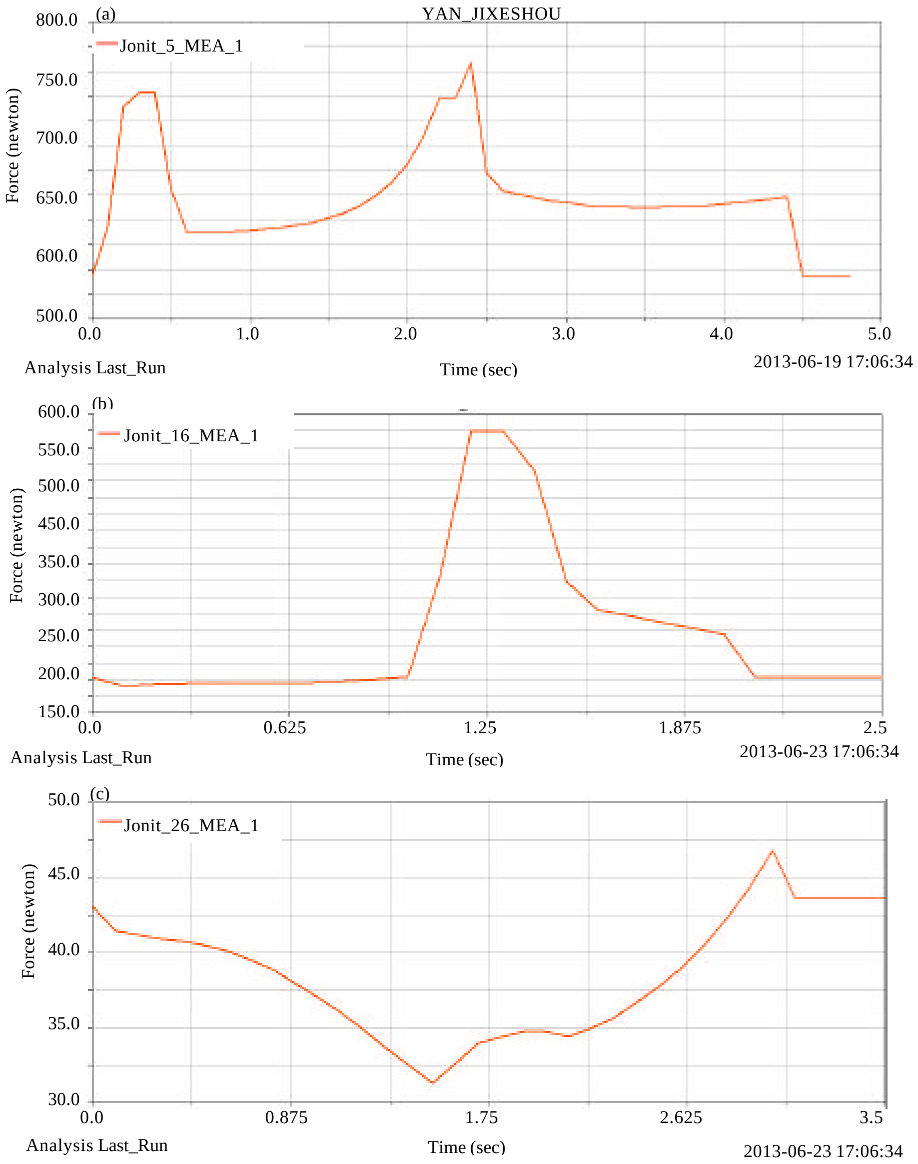

Fig. 17(a-c): Active joint constraint reaction force curves, (a) Master hand, (b) Positioning hand and (c) Adjusting hand

CONCLUSION

Clamping manipulator of offshore drilling platform is introduced in this study. Theoretical calculation and analysis and ADAMS simulation of its kinematics and dynamics are also realized. Some conclusions as follows are obtained:

- The kinematics analysis of clamping manipulator indicates that a certain motion relationship of system will be obtained when a constant condition is given because each group of manipulator has only one degree of freedom. If velocity and acceleration of manipulator that is obtained by the simulation is consistent with actual data, it can be used as an important basis of manipulator control system design
- The theoretical dynamic model of clamping manipulator is a classic analysis way of kinematics and all constraints are ideal constraints. As a result of fixed constraint of slide pair and manipulator formed by piston is not on same straight line, more complex kinematic relations appear, the result of ADAMS

simulation could be more closer to actual working condition, the calculation method is very different with traditional method and the result has more reference value

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