Finite Element Analysis Based Design of Mobile Robot for Removing Plug Oil Well

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***Abstract*—In order to develop the mobile robot for removing the plug oil well, the robot was designed based on the wheel-type and leg-type robot mechanism. A well functioning prototype has been manufactured. To demonstrate the validity and the benefit of the mobile robot, supporting mechanism and guiding rod were chosen to design based on the FEM. The mathematical model of the supporting mechanism is established and the mechanical property is analyzed using the FEM. The deformation and stress of some components of the supporting mechanism and the guiding rod is investigated. The results show that the supporting mechanism and the guiding rod have excellent performance with little displacement and small stress under working condition. The strength and rigidity of supporting mechanism and the guiding rod are good enough to ensure the reliability of the whole robot mechanism.**

***Index Terms*—Mobile robot; Oil well; FEM; Supporting mechanism**

I. Introduction

Mobile robots have been widely used to carry out manifold tasks such as industrial applications, planetary exploration, rescue operation and medical services in recent years. In the oil and gas field, there are a lot of pipes that need to be detected and rescued, which promote the development of the mobile robots.

Most reservoirs in the oil field are low permeability because of oil reservoirs pollution, scale formation, paraffin deposit and so on. The low permeability usually causes the reduction of oil production [1, 2]. Accordingly the technology of removing plug oil well has become a important guarantee to protect oil reservoirs, improve oil production and oil recovery ratio [3]. The technology of removing plug oil well manly includes the chemical removing plug oil well and physical removing plug oil well. The plug removal technology with electrical pulse for oil reservoir is a new method developed to solve the problem of oil well plugging. It uses a mobile robot putting positive and negative electrodes into the perforation and loads discharge pulse on them generated by pulse power. Owing to the special work condition of the mobile robot, the design of the robot is very important.

According to a locomotive mechanism to achieve the desired mobility, mobile robots may be split into following categories: leg-type, track-type and wheel-type mobile robots. While the leg-type mobile robot ensures the most superior adaptability to all kinds of environments, its mechanism is quite complicated because active control algorithms equipped with additional actuators and sensors are required to steadily maintain its balance, which inevitably leads to slow movement and poor energy efficiency [4, 5]. The track-type mobile robot provides acceptable mobility on an off-road environment by virtue of its inherently stable mechanism. However, the excessive friction is lost during changing a direction, which also results in poor energy efficiency [6]. Compared to other alternatives, the wheel-type mobile robot can be developed in the simplest configuration. Therefore the fast movement as well as good energy efficiency is guaranteed without any complicated control strategy. However, its adaptability to an environment does not seem to be sufficiently good and its mobility is restricted depending on both the type and the size of encountered obstacle [7].

Therefore, it is not surprising that high mobility on various environments have been a primary factor among others when evaluation the performance of the mobile robot. Li Peng et al. [8] proposed an adaptive mobile robot which had the adaptability to the change of pipe diameters. When the robot encounters a step, the adaptive mobile mechanism of the robot will change its working mode to surmount the obstacle. Compared to classical screw-driven robots, this robot does not employ the link-type configuration, but only uses one actuator to solve the low capability of surmounting obstacle. The observed rotation problem of the supporting parts is solved by the kinematical analysis of the robot. Joshi et al. [9] designed a spherical mobile robot, rolling on a plane with the help of two internal rotors and working on the principle of conservation of angular momentum. The robot is a classic nonholonomic system. The kinematic model of the

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doi:10.4304/jcp.8.6.1504-1511

system is developed using quaternion for the description of the orientation of the robot. The model is fully controllable and can be taken from any arbitrary configuration to any arbitrary configuration within the unit 3-sphere in the quaternion space. Kim et al. [10] presented an optimal design of a wheel-type mobile robot having high mobile stability as well as excellent adaptability while climbing stairs. The Taguchi method is adopted as an optimization tool and the sensitivity analysis with respect to design parameters is carried out to provide an insight to their effects on the performance criterion under kinematic constrains which are imposed to avoid undesired interference between a mobile robot and stairs. Aracil et al. [11] proposed the parallel robots for autonomous climbing along tubular structures and studied the dynamics of some different configurations. The parallel robot is based on the application of the Gough-Stewart (G-S) platform. Technical specifications of the system are presented and the control scheme is analyzed. Several experiments have been carried out and the analysis of the results has checked the high capacity of the parallel robot to climb on tubular structures with unknown trajectories.

Based on the wheel-type mobile mechanism, an optimal design of the mobile robot for removing the plug oil well is presented. A well functioning prototype has been manufactured. Section 2 describes the structure of the mobile robot including micro-step walking mechanism, revolving measuring mechanism, and EDM removing plug mechanism. Section 3 presents the mathematical and FEM models for the supporting mechanism. Section 4 gives the analysis results. And Section 5 summarized the paper.

II. Structure principle of the robot

A. The Whole Mobile Robot System

To remove the plug oil well, the technology of EDM (electrical discharge machining) removing plug well is proposed in this paper. And the mobile robot is developed for this technology. The wheel-type robot has the simplest configuration and the fast movement. The leg-type mobile robot has the most superior adaptability to all kinds of environments. Based on the merits of the wheel-type and leg-type robot, the mobile robot mechanism is designed to use in the oil pipe. Considering the rigors environments of the oil pipe, the configuration of the mechanism should be simple, small sizes, flexibility and reliability. Therefore the prototype of mobile robot has been manufactured in the laboratory. The whole mobile robot system for removing the plug oil well is shown in Fig.1 (a).

As shown in Fig.1 (b), the mobile mechanism is mainly composed of micro-step walking mechanism, revolving measuring mechanism, and EDM removing plug mechanism. When the oil pipe is plugged, the moving robot is tripped into the oil pipe under several kilometers by the drawworks. Once the robot arrives at the designated position, the drawwoks will stop working. Then the micro-step walking mechanism will start moving to search for the perforating position because the designed position is not the perforating position exactly. The robot crawls along the inner surface of the oil pipe by the micro-step walking mechanism; and the revolving measuring mechanism rotates to detect the perforating position according to the sensors at the same time. Once the perforating position is detected, the robot will stop moving and halted in the oil pipe. And then the EDM removing plug mechanism will remove the plugged objects under the enormous discharge energy. Moreover the movement of robot is controlled by the remote control system and the whole working process can be monitored on the ground.

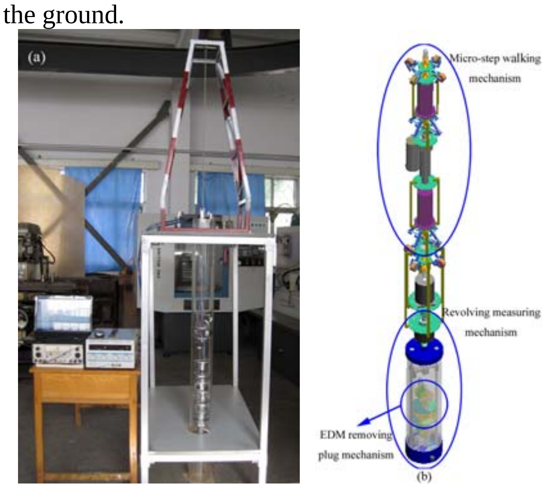

Figure 1. Schematic diagram of the mobile robot.

B. Micro-step Walking Mechanism

The micro-step walking mechanism is one of the main members of the mobile robot. It can enable the mobile robot walk and stop in any position of the vertical oil pipe. It also can guide and centralize the robot in the pipe. Moreover it can be adaptive to different diameters of the pipe.

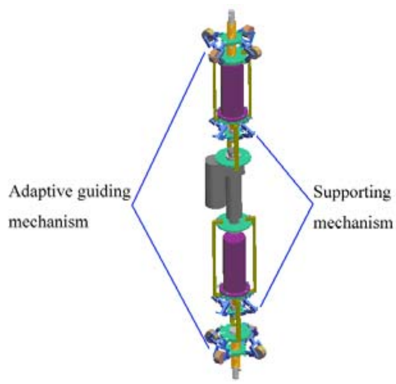

Figure 2. Micro-step walking mechanism

As shown in Fig 2, the micro-step walking mechanism contains two sets of adaptive guiding mechanism, supporting mechanism and electric telescopic rod. Based on the principle of slider-crank mechanism, the adaptive guiding mechanism has four cranks distributed for 90° that are opened by the slider pushing at the effect of the pretightening force of spring. It can be self-adaptive to different diameters of pipe. The tension wheels are installed on the adaptive guiding mechanism to reduce the friction force and help the robot tripped into the oil pipe smoothly. The supporting mechanism is composed of four supporting legs distributed for 90° and controlled by the electric telescopic rod. The electric telescopic rod can push the supporting legs of the supporting mechanism on to the inner surface of the pipe. And the friction force between supporting legs and pipe is large enough to ensure the robot hovering steadily for a long time. The electric telescopic rod also can control the distance per step while the robot walking, which is changed by controlling its telescopic direction and turn-on time.

C. Revolving Measuring Mechanism

The revolving measuring mechanism is responsible for detecting the perforating location in the oil well and can revolve 360° in the pipe, which makes the measuring sensor detect the circumferential surface of the pipe. The revolving mechanism is manly composed of step motor, supporting bearing, shaft coupling and conducting slip ring, as shown in Fig 3(a). It can be revolved by the step motor and transmitted motion by the shaft coupling. The conducting slip ring is an important part to transmit the signals among the revolving parts with the non-revolving parts. There are four connecting rods between the step motor and the conducting slip ring. This can ensure the steady and centralization of the revolving measuring mechanism.

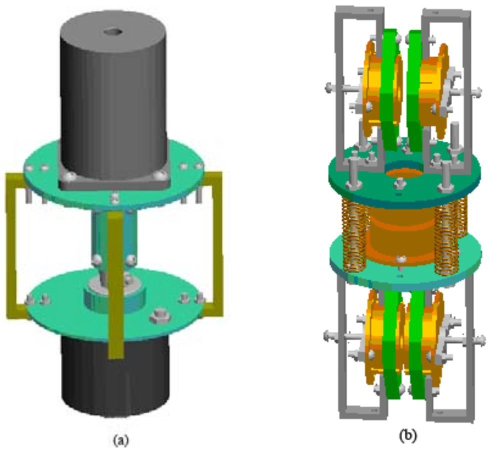

Figure 3. (a) Removing measuring mechanism; (b) EDM removing plug mechanism.

Moreover the lower part of the revolving measuring mechanism is attached with the measuring sensor and the EDM removing plug mechanism distributed symmetrically, as shown in Fig 3(b). When the perforating location is detected, the revolving measuring mechanism will rotate 180° and the EDM removing plug mechanism is in alignment with the perforating location exactly. The measuring work is mainly depending on the electric eddy current sensor which is a non-contacting sensor and produces the output signals according to the eddy current. So the removing plug work can be carried out. The removing plug work is mainly completed by the electric discharge between the electrodes. And the power supply on the ground provides the discharge voltage and current. The EDM removing plug mechanism feeds on the tool electrode wire used for removing plug continuously. This can compensate the removed tool electrode during the plug removing process. In one word the revolving measuring mechanism should have higher positioning accuracy to ascertain the detection of the perforating location.

III. Mechanical Model for the Supporting Mechanism

A. Mathematical Modeling

It is worthwhile to consider the static analysis on the robot mechanism so as to meet the requirement of the strength and rigidity of the whole mechanism. The supporting mechanism is composed of four pairs of supporting legs distributed for 90°, the upper supporting plate, and the lower supporting plate. The upper supporting plate is fixed with the electric telescopic rod by nut, whose position could not be moved. However the lower supporting plate is mobile, which is fixed with the central pole of the electric telescopic rod by nut. Through adjusting the nut of the lower supporting plate, the mobile robot can be adaptive to various diameters of pipe. The central pole of electric telescopic rod moves up and down by controlling the power on and off of the electric telescopic rod. Therefore the supporting mechanism can be opened to the pipe wall and enable the whole mobile robot stop in the vertical oil pipe.

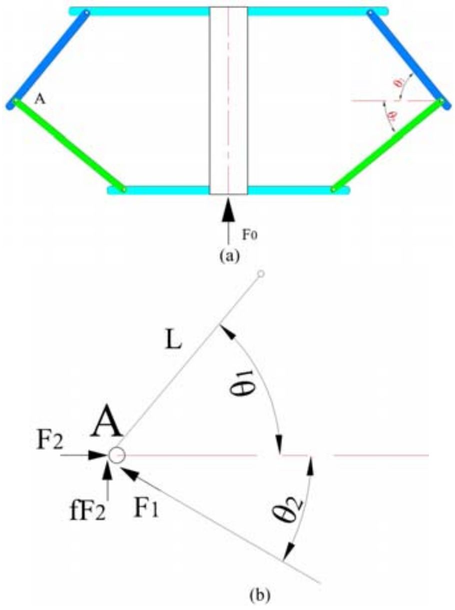

Figure 4. Mathematical modeling of the supporting mechanism (a) simplified model of the supporting mechanism; (b) mechanical analysis of connecting pin A.

The supporting mechanism is the most important component in the whole robot mechanism and ensures the stability of the whole mechanism. It endures the gravity of the whole mechanism, the supporting force of the pipe wall and the friction force. In order to analyze the interaction forces between the supporting mechanism and the pipe wall during the EDM removing plug mechanism working condition, we established the mathematical model. Considering the symmetry of the mechanism, the mathematical model is simplified as shown in Fig. 4(a). The supporting leg could be simplified to the two-force bar [12-14]. The force on the pin A that is contacted with the pipe wall is analyzed in Fig. 4(b). According to the principle of force balance, the force can be expressed as

$$\sum F(0) = F_x + F_y = 0 \quad (1)$$

$$F_x = F_2 \times L \times \sin(\theta_1) - F_1 \times \sin(\theta_1 + \theta_2) \times L \quad (2)$$

$$F_y = f \times F_2 \times \cos(\theta_2) \quad (3)$$

$$F_1 = F_0 / 2\sin(\theta_2) \quad (4)$$

Where F is the resultant force; F_0 is the force produced by the spring on the lower supporting plate; F_1 is the supporting force of the supporting leg; F_2 is the force on the supporting mechanism by the pipe wall, L is the length of the upper supporting leg, f is the friction coefficient between pipe wall and supporting mechanism; θ_1 is the angle of the upper supporting leg to the horizontal line; θ_2 is the angle of the lower supporting leg to the horizontal line.

The force on the supporting mechanism by the pipe wall F_2 can be achieved by Equation (1), (2), (3) and (4) and expressed as

$$F_2 = \frac{F_0 \sin(\theta_1 + \theta_2)}{2(\sin\theta_1 - f\cos\theta_2)} \quad (5)$$

From Equation (5), the force on the supporting mechanism by the pipe wall F_2 is related to the force produced by the spring on the lower supporting plate F_0 and the angle of the upper supporting leg to the horizontal line θ_1, the angle of the lower supporting leg to the horizontal line θ_2. And it has the maximum value only when the sum of θ_1 and θ_2 is the largest and sinθ_1 is almost equal to cosθ_2.

B. FEM Modelling

FEM software is used to simulate and analyze stress and deformation of the supporting mechanism to ensure the strength and rigidity of the whole robot mechanism. When the mobile robot arrives at the perforation position, the electric telescopic rod is power on and the supporting legs are supported onto the pipe wall. The whole robot mechanism is hovered in the oil pipe steadily and the EDM plug mechanism starts to work. Therefore the supporting mechanism should have enough supporting force to support the whole mechanism. The forces on the supporting mechanism are mainly the electromagnetic force, the gravity and the acting force with the pipe wall. Therefore the electromagnetic force and the gravity can be simplified to the force acted on the upper and lower supporting plates only.

The finite element model of the supporting mechanism is established using the 3-D modeling element SOLID98 as shown in Fig. 5. The high precision element SOLID98 is adopted to analyze the stress and deformation. It is because that the SOLID98 element is a ten nodes Tetrahedral element and more suitable for producing the irregular shape grid [15, 16]. In addition, the guiding rod is introduced to be analyzed the stress and deformation based on FEM. The guiding rod is throughout the supporting mechanism (shown in Fig. 1 (b)) and places an important role at the aspect of guiding and supporting the whole robot mechanism. Its strength and rigidity can ensure the stability of the whole robot mechanism. Stainless steel and aluminium alloy are considered for simulation in the FEM models because the supporting mechanism is manufactured with stainless steel and the guiding rod is manufactured with aluminium alloy. The stainless steel has the merit of high strength and the aluminium alloy has the merit of light weight [17, 18]. The boundary conditions are fixed on the models and static analyses are performed in sequence in order to obtain the analysis results of the stress and deformation of the components.

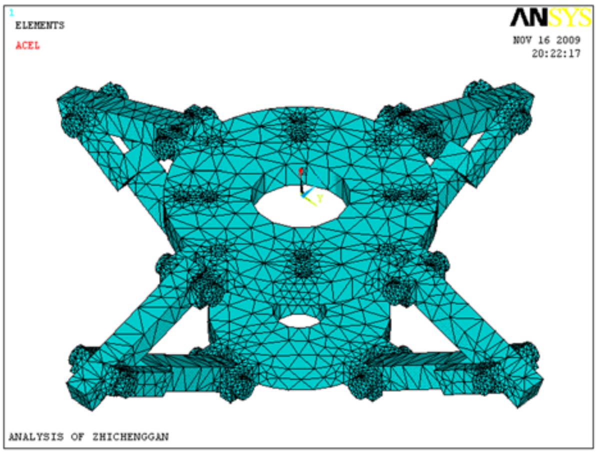

Figure 5. FEM model of the supporting mechanism

IV. Results and Discussion

A. Displacement and Stress of the Upper Supporting Plate

The upper supporting plate is round and has four connecting pins with the upper supporting legs. And it is stationary fixed with the electric telescopic rod. So it manly bears the forces of the upper supporting legs when the supporting mechanism is supported on to the pipe wall. Under the effect of the electromagnetic force and gravity, the displacement of the upper supporting plate is shown in Fig. 6 (a). The maximal deformation emerges at the connecting points with the upper supporting legs. This is mainly owing to the weight of the whole mechanism that ultimately caused the connecting points buckled. Therefore the rigidity of the connecting points should be improved. And the manufacture of the connecting points could adopt the special machining technology or the material used could be the high strength materials different from the round supporting plate. The stress of the upper supporting plate is shown in Fig. 6 (b). It can be seen that the stress value of the upper supporting plate is very small and the maximum value is only 8.85Mpa, which only emerges in minor places. The stress value is much smaller than the allowable stress of material. Therefore the thickness of the upper plate can be reduced properly.

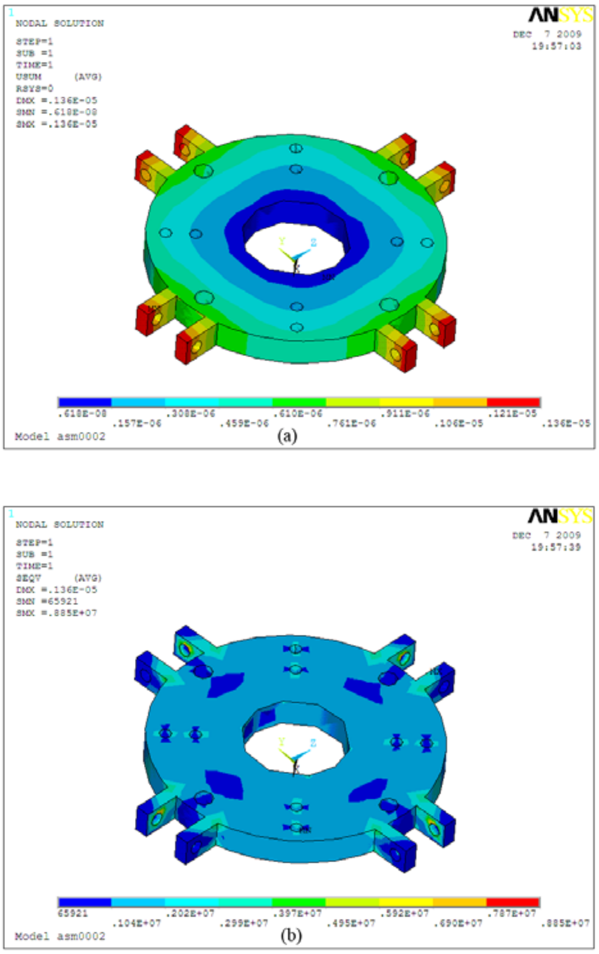

Figure 6. Simulation results of the upper supporting plate (a) displacement (b) stress.

B. Displacement and Stress of the Upper Supporting Leg

The support and steady effect of the supporting mechanism mainly depends on the upper and lower supporting legs supporting on to the pipe wall. The upper supporting leg is connected to the lower supporting leg by pins. So the upper leg moves with the movement of the lower leg. Therefore the force of upper supporting leg mainly comes from the lower supporting leg.

In this FEM analysis it is supported that the displacement between the upper supporting leg and the inner pipe wall is zero. And the maximal displacement of the upper supporting leg emerges at the intermediate section as shown in Fig. 7 (a). It is concluded that the upper supporting leg is liable to produce bending deformation and the material of the upper supporting leg can be chosen to the better material with high strength. Obviously, the upper supporting leg is a mainly forcing component and bears the effect of electromagnetic force. So the supporting arm could produce larger stress as shown in Fig. 7 (b). And the greatest stress value is to 56Mpa which also meets the strength requirement. The greatest stress is mainly distributed in the contacting places with the pipe wall. The stress between upper supporting leg and lower supporting leg is also very large. Therefore the materials with high strength and light weight will be a better chose for the upper supporting legs.

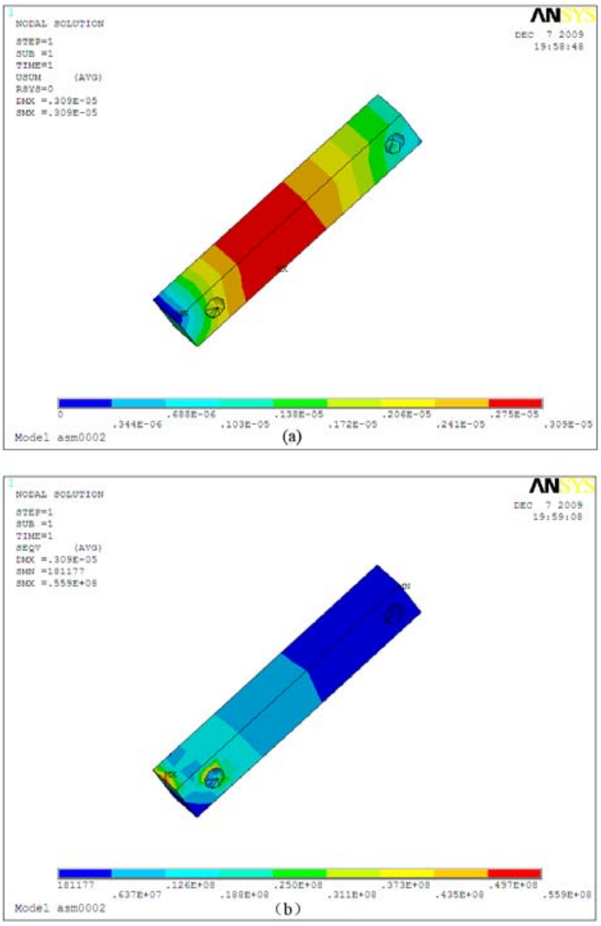

Figure 7. Simulation results of the upper supporting leg (a) displacement (b) stress.

C. Displacement and Stress of the Lower Supporting Leg

The lower supporting leg is another important supporting component of the supporting mechanism. It is connected with the lower supporting plate and moves by the pushing of the lower plate. Therefore the force of lower supporting leg mainly comes from the lower supporting plate. The shape of the lower supporting leg is different from the upper one. It is used to support the upper leg.

The lower supporting leg could be regarded as a two force bar whose force is in the direction of its application. Therefore the deformation of the lower supporting leg is in the direction of its application. As shown in Fig. 8 (a), the maximal displacement of the lower supporting leg emerges at the connecting joint with the lower supporting plate. The lower supporting leg is mainly under the effect of the compressive force coming from the lower plate because it moves with the movement of the lower supporting plate. As shown in Fig. 8 (b), the maximum stress is produced at the pins connecting place. The stress is a little greater due to the effect of the electromagnetic force by the lower supporting plate. And the greatest value is 48.8Mpa which also meets the strength requirement. In general, the size of the lower supporting leg is suitable and the displacement and the stress based on FEM are in the reasonable scope.

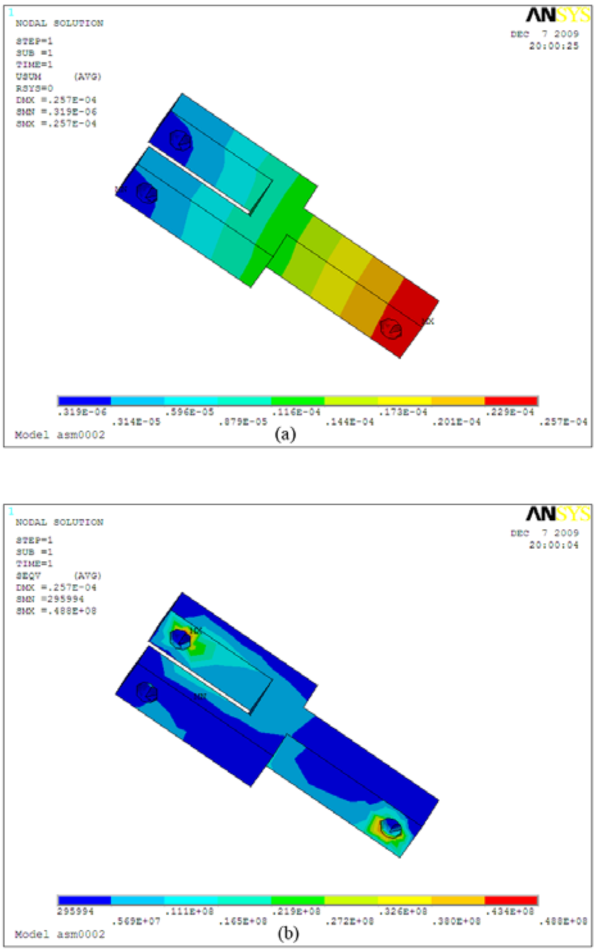

Figure 8. Simulation results of the lower supporting leg (a) displacement (b) stress.

D. *Displacement and Stress of the Lower Supporting Plate*

Comparing to the upper supporting plate, the lower supporting plate has a smaller size and is moveable. It is fixed with the central pole of the electric telescopic rod and moves up and down by controlling the power on and off of the electric telescopic rod. Under the movement of the lower supporting plate, the supporting mechanism can be adaptive to many sizes of pipe. So it manly bears the electromagnetic force from the electric telescopic rod when the supporting mechanism is supported on to the pipe wall.

The maximal deformation of the lower supporting plate emerged at the centre as shown in Fig. 9 (a), which is differently from the deformation of upper supporting plate. This is because that the electromagnetic force and gravity is directly put on the centre of the lower supporting plate. Therefore the lower supporting plate should have sufficient rigidity. As shown in Fig. 9 (b) the stress of the lower supporting plate is almost distributed uniformly at about 0.56Mpa. But the maximal stress value of is to 56.1Mpa. This only emerges at the connecting place. Also the stress concentration appears at the sharp angle. Therefore, the high rigidity material should be chosen to machine this part. And the sharp angle should be filleted to reduce the stress concentration during machining.

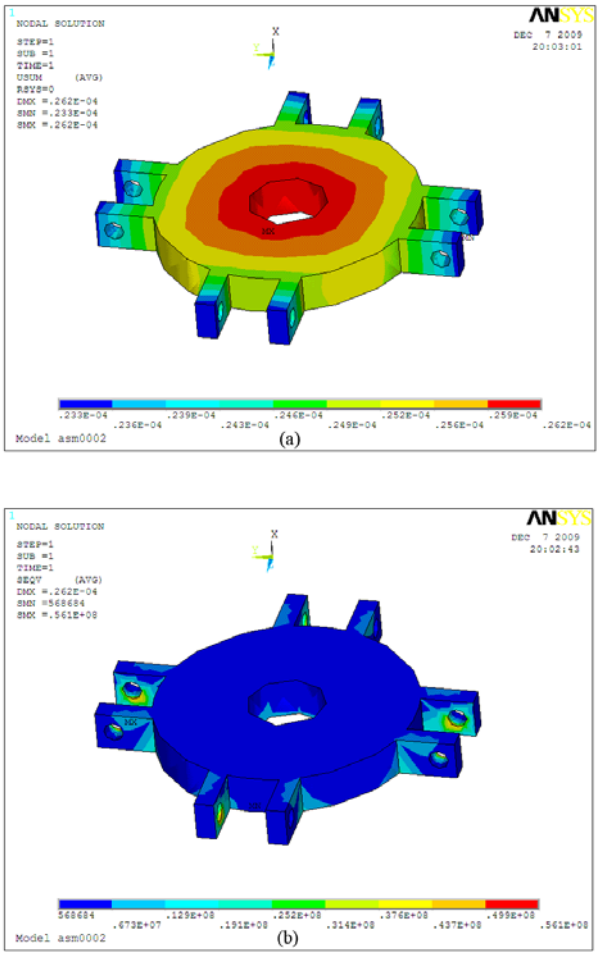

Figure 9. Simulation results of the lower supporting plate (a) displacement (b) stress.

E. *Displacement and Stress of the Guiding Rod*

The guiding rod is located at the upper part of the whole robot and throughout the supporting mechanism. It is a centre rod to hold the stability and the verticality of the whole mechanism. It also bears the weight of the whole mechanism and belongs to a bearing bar. There are two holes on the guiding rod as shown in Fig. 10. The upper one is used to fix the cables and the lower one is used to install the spring retainer ring. When the robot in tripped into the oil pipe, the guiding rod bears the pulling force of the cable and the gravity of the whole mechanism; when the robot is hovered in the oil pipe, it manly bears the gravity.

Before developing the mathematical optimum model of the guiding rod, the following assumption are made that the gravity of the whole robot is changed into the compressive force that is acted on the outside of the guiding rod lower part. So the 10kg force was acted on the guiding rod. According to the static analysis, the deformation and stress of the guiding rod is shown in Fig. 10 (a) and Fig. 10 (b). The guiding rod mainly bears a tensile force and the deformation increases gradually from the up to down. Finally, the deformation is up to the maximum value of 0.0021mm at the lower part of the guiding rod. The material of the guiding rod should have enough tension strength. At the intermediate section of the guiding rod, the stress value is almost the same. However, at the two ends the stress value is a little smaller. And the maximal stress of 8.96Mpa emerges at the lower part. The maximum stress value is smaller than the allowable stress of aluminum alloy. Therefore it can meet the requirements of strength and rigidity.

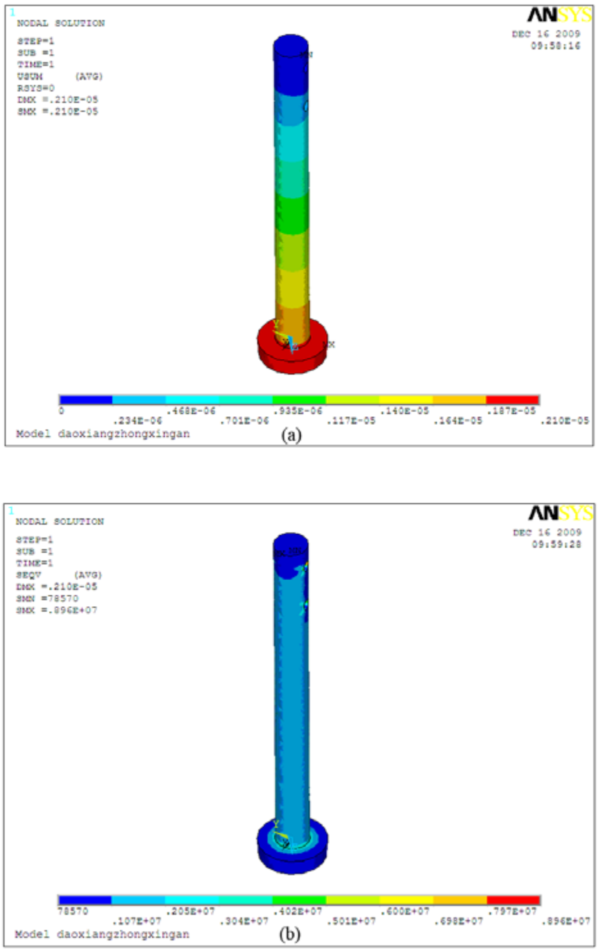

Figure 10. Simulation results of the guiding rod (a) displacement (b) stress.

The simulation results of the guiding rod under the force of 10Kg have been obtained above. Considering the working condition, different forces has been acted on the guiding rod to study its deformation. Also the diameter of the guiding rod is changed from 6mm to 12mm. The deformation of different sizes guiding rod under the force of 5Kg to 25Kg is shown in Fig. 11. The deformation increases with the increasing of the force linearly at the same guiding rod diameter. With the increasing of the diameter, the deformation is also increasing. Moreover the deformation difference with different sizes is more obvious when the force is very large. The maximum value of deformation increases from 0.0015mm to 0.00526mm as the force increase from 5Kg to 25Kg. However, the deformation value is very small, which has no influence to the whole mechanism.

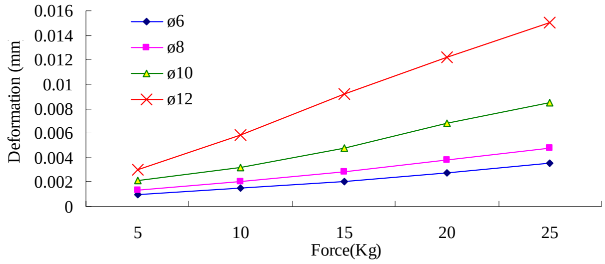

Figure 11. Simulation results of the guiding rod deformation under different forces

V. CONCLUSIONS

A mobile robot for removing the plug oil well is presented in this work and the prototype has been manufactured. The mechanical model and FEM model of the supporting mechanism is established. The deformation and stress of the upper supporting plate, the upper supporting leg, the lower supporting leg, the lower supporting plate and the guiding rod are analyzed.

(1) The mobile robot for moving the plug oil well is designed based on the wheel-type and leg-type mobile mechanism and adaptive to various pipe sizes. The robot has the merits of simple structure, easy operation, good adaptability and reliability.

(2) The Mathematical model of the supporting mechanism is established according to the force balance under the EDM removing plug mechanism working condition. The force of the supporting mechanism with the pipe wall can be obtained.

(3) Based on the FEM, some components of the supporting mechanism are analyzed. The results of finite element analysis indicate that the maximum deformation of upper supporting plate emerges at the pins connecting place, the maximum deformation of upper supporting leg emerges at the intermittent section, the maximum deformation of lower supporting leg emerges at the pins connecting place and the maximum deformation of lower supporting plate emerges at the centre. And the stress of the components is all at the range of the allowable stress of materials.

(4) The guiding rod of the robot is also analyzed based on the FEM. And the results prove that the guiding rod has a small deformation and allowable stress value. It can meet the requirements of strength and rigidity. The whole robot mechanism has a good performance.

ACKNOWLEDGMENT

The authors wish to acknowledge the financial support of National High-Technology Research and Development Program of China (No.2007AA09A101), National Natural Science Foundation of China (No.50874115), Taishan Scholar project of Shandong Province (TS20110823), Science and Technology Development Project of Shandong Province (2011GHY11520) and

Fundamental Research Funds for the Central Universities (11CX04031A).

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