Analysis of Contact forces for Forging Manipulator Grippers

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Abstract—whether the gripper of a forging manipulator can achieve stable gripping depends a lot on the position and constraints of contact points. Therefore the analysis of contact status between the gripper and work piece is very important for the evaluation of the capability and reliability of the forging manipulator. In this paper, the contact forces of static stable gripping are analyzed by space decomposition method for a forging manipulator loading work-piece of 250kg. The dynamic simulations are also used to analyze the contact status of gripping. The improvements of stable gripping are then given. The above analysis provides a good foundation for the optimization of the structure and the design of the control system of the forging manipulator.

Keywords— forging manipulators, gripping, contact forces, stability

I. INTRODUCTION

A forging manipulator plays a very important role in achieving mechanization and automation of forging [1]. The reliability and safety of the equipment depend upon the stable gripping of the work piece during motion. Whether the gripper of a forging manipulator can achieve stable gripping depends a lot on the position and constraints of contact points. Thus the analysis of contact status between the gripper and work piece is necessary for the design of a forging manipulator.

In this paper, the contact forces are studied based on the static contact forces calculation through space decomposition [2] for a forging manipulator loading normal 250kg work-piece. The analytical results are illustrated by dynamic simulations.

II. STATIC CONTACT FORCE MODELING

Fig.1 shows a simple model for static contact force calculation. Assume that the system is rigid and is of frictionless point contact. The contact forces between the gripper and work piece have the relation to the external wrench and the joint torque of grippers which is determined by equilibrium equations as follows [3].

$$Gf = \mathbf{w}, \qquad (1)$$

and

$$J^T f = \tau. \qquad (2)$$

Where G －grasp matrix

J－ Jacobian matrix of the hand

$w \in R^6$ －external wrench on work piece

$\tau \in R^m$ －joint torque on hand with m being the number of joints

$f \in R^n$－ contact forces on work piece with n being the number of contact constraints.

It is assumed that the null spaces of grasp matrix and Jacobian matrix have intersection. From(1) and (2), the vector space of contact forces $\Gamma \in R^n$ can be decomposed into four subspaces defined as follows [3].

$$\begin{cases} \Gamma_{h2} = \left\{ f_{h2} \middle| f_{h2} \in N(G) \cap N(J^T) \right\} \\ \Gamma_{h1} = \left\{ f_{h1} \middle| f_{h1} \in N(G), f_{h1} \notin N(J^T) \right\} \\ \Gamma_{p2} = \left\{ f_{p2} \middle| f_{p2} \notin N(G), f_{p2} \in N(J^T) \right\} \\ \Gamma_{p1} = \left\{ f_{p1} \middle| f_{p1} \in N(G), f_{h1} \notin N(J^T) \right\} \end{cases} \qquad (3)$$

Where N (G) is the null space of grasp matrix and $N(J^T)$is the null space of Jacobian matrix. Correspondingly the contact force is formulated as [3]

$$f = f_{p1} + f_{p2} + f_{h1} + f_{h2}. \qquad (4)$$

Where f_{p1} is the active grasping force that generates a resultant wrench and is controlled by joint torques, if $f_{p1}=0$, it shows that the grippers cannot be manipulated; f_{p2} is the passive gripping force that generates a resultant wrench but is not controlled by joint torque; f_{h1} is the controllable internal force that does not generate a resultant wrench but is controlled by joint torques; f_{h2} is uncontrollable internal force that neither generates a resultant wrench nor is controlled by joint torques.

“973”project (2006CB705400) supported by National Basic Research Program of China

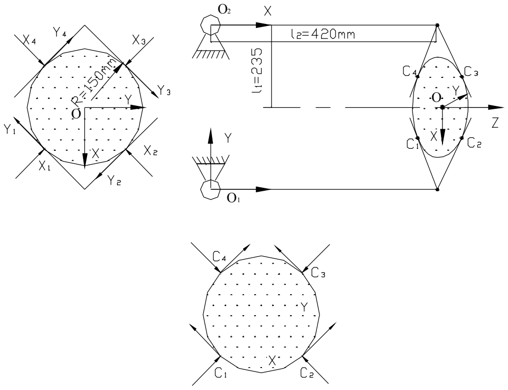

Figure 1. grippers model

The parameters of the gripping contact model are given in table Ⅰ. For the gripping model shown in Fig.1 (a), the grasp matrix and Jacobian matrix are as follows.

$$G=\begin{pmatrix} -\frac{\sqrt{2}}{2} & -\frac{\sqrt{2}}{2} & -\frac{\sqrt{2}}{2} & \frac{\sqrt{2}}{2} & \frac{\sqrt{2}}{2} & \frac{\sqrt{2}}{2} & \frac{\sqrt{2}}{2} & -\frac{\sqrt{2}}{2} \\ \frac{\sqrt{2}}{2} & -\frac{\sqrt{2}}{2} & -\frac{\sqrt{2}}{2} & -\frac{\sqrt{2}}{2} & -\frac{\sqrt{2}}{2} & -\frac{\sqrt{2}}{2} & \frac{\sqrt{2}}{2} & \frac{\sqrt{2}}{2} \\ 0 & -R & 0 & -R & 0 & -R & 0 & -R \end{pmatrix}$$

$$J^T=\begin{pmatrix} \frac{\sqrt{2}}{2}(l_2-l_1) & 0 \\ \frac{\sqrt{2}}{2}(l_2+l_1) & 0 \\ \frac{\sqrt{2}}{2}(l_2+l_1) & 0 \\ \frac{\sqrt{2}}{2}(l_1-l_2) & 0 \\ 0 & \frac{\sqrt{2}}{2}(l_2+l_1) \\ 0 & \frac{\sqrt{2}}{2}(l_1-l_2) \\ 0 & \frac{\sqrt{2}}{2}(l_1-l_2) \\ 0 & \frac{\sqrt{2}}{2}(l_2+l_1) \end{pmatrix}$$

Other parameters are determined by equilibrium equations as follows [3].

$$N_i=\dim N(G^T) \qquad N_r=\dim N(J) \quad (5)$$

$$M=m+6-\operatorname{rank}(A) \quad (6)$$

$$N_c=M-N_r \quad (7)$$

Where N_i- indeterminacy N_r- redundancy

M-degree of freedom N_c- activity

dim -dimension of space A-$(G \quad J^T)^T$

TABLE I. PARAMETERS OF STATIC CLAMP CONTACT MODEL

Joints number	Contact constraints	Contact points
m=2	n = 12	4

By calculation, one has

$$N_i=0; \quad N_r=0; \quad M=3; \quad N_c=-3.$$

According to the above results, the gripping between the gripper and work piece is over constraint. The dimension of four subspaces can be obtained as follows [3].

dim Γ p1=0; dim Γ p2=3; dim Γ h1=m=2; dim Γ h2= -NC=3.

Therefore, the contact forces can be written as $f=f_{p2}+f_{h1}+f_{h2}$, which can be determined as follows.

$$f=\begin{pmatrix} 1 & 4 & 1 \\ 1 & -1 & 1 \\ 6 & -1 & -1 \\ -1 & -2 & 2 \\ 0 & 1 & 0 \\ 0 & -5 & 4 \\ 1 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix}\alpha+\begin{pmatrix} 1 & 0 \\ 0 & 1 \\ 0 & 1 \\ 1 & 0 \\ 0 & -1 \\ -1 & 0 \\ -1 & 0 \\ 0 & -1 \end{pmatrix}\beta+\begin{pmatrix} 1 & 1 & -1 \\ -1 & 0 & 1 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & -1 \\ 0 & -1 & 0 \end{pmatrix}\gamma \quad (8)$$

where $\alpha, \gamma \in R^3$, and $\beta \in R^2$.

The contact model (8) shows that f_{p1} is equal to 0, so the grippers cannot be manipulated. The existence of contact force f_{p2} means that this system can passively resist external wrench along f_{p2} direction shown in Fig.1. Contact force f_{h1} can be provided by joint torque which cannot resist external wrench, but it can increase the friction by means of increasing press on work piece. This friction is good for gripping stability. According to calculation, we found that all contact forces of the gripper cannot resist force along work piece axis or torque about y axis in stable gripping status as shown in Fig.2 (a).

Usually, a gripper is designed so that it can rotate around fixed pins freely in order to be more useful and better positioning. Therefore counteractive force on the gripper will cause rotation around the fixed pins which result work piece away from its horizontal axis and sliding of contact points. The rotation and sliding would not stop until resultant friction force F_i along axis and contact force N_i passes the center of the fixed pins. Then the system approaches equilibrium as illustrated in Fig.2 (b).

III. DYNAMIC SIMULATION INS

Gripping constraints have been analyzed above. However, contact constraints are more complex especially when sliding exists between the work piece and the grippers. Thus dynamic simulation tool ADAMS is used to study the contact status between the gripper and work piece.

A. *Dynamic modeling*

Fig.3. shows the three-dimensional model of the forging manipulator which is created in ADAMS/VIEW. The operation process includes gripping, lifting and rotating of the gripper. Dynamic simulation parameters are set in tableⅡ.

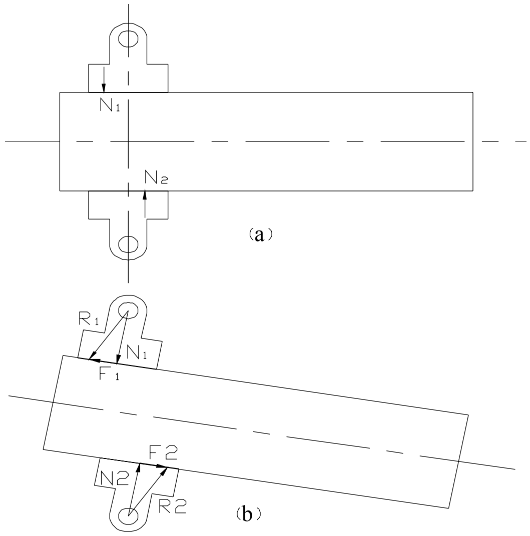

Figure 2. contact status

The dynamic process is set as follows, gripping work piece (0s~2s), lifting work piece (2s~4s) and rotating 360 degrees (6s~16.5s).

B. Result analysis

The 3d-space positions of the contact points between the gripper and work piece when gripping are shown in Fig.4. And curves of contact forces of the given points and the driving forces of the gripping cylinder during a forging process are shown in Fig.5. In Fig.4, fourteen different contact points are obtained through Adams simulations during one working cycle. As illustrated in Fig.5, contact points work alternatively during the motion cycle, the force contact is zero if the gripper and work piece does not contact. Major working points are 1-7,1-8,1-11,1-12 on upper part of the gripper and 2-5, 2-6, 2-8, 2-9 on lower part of the gripper during the period of gripping, rotating and lifting.

The simulation results show that these fourteen points do not work continuously. It means that the contact position of the gripper changes during working process and sometimes contact forces disappear during rotating period. This undulation phenomenon can be explained based on the analysis of contact force from formula (8). According to the contact force decomposition model of equation (8), contact forces cannot balance big moment caused by long work piece as gripper is designed so that it can rotate around the fixed pins freely. Thus,

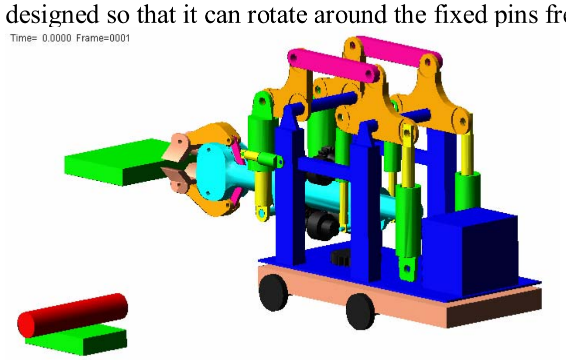

Figure 3. Three-dimensional model of the forging manipulator

TABLE II. PARAMETERS OF DYNAMIC SIMULATION

material	steel	**Penetration depth**	0.1
Mass (work piece)	250kg	**Damping coefficient**	1.0×10^{2}
Length(work piece)	2.4m	**Static coefficient of friction**	0.5
Stiffness coefficient	1.0×10^{5}	**Dynamic coefficient of friction**	0.3
Stiffness force exponent	2		

the recoil force on the gripper leads to rotation around the fixed pins which results in work piece rotation and sliding between the gripper and work piece. As a result, the contact points change. In terms of the equilibrium equations (1) and (2), grasp matrix G and Jacobian matrix J change at different points. This is because the contact forces space changes. During the rotating period, the contact status changes from Fig.2 (a) to Fig.2 (b). Obviously the position of contact points changes a lot, resulting in that contact forces disappear. Furthermore, changes of contact forces from the grippers will lead to the active driving forces of the whole forging manipulator follow its changes, and the dynamic characteristics of the forging manipulator is changed. Contact force undulation will cause output driving force (torque) unsteady as shown in Fig.5.

IV. IMPROVEMENTS STABLE GRIPPING

The undulation of both contact forces and output driving force affects stable gripping and control of forging manipulators. Therefore, it is necessary to find some possible measures for improvement.

Consider that the gripper rotation around the fixed pins is the major cause of the undulation of contact forces. Simulations using ADAMS show that the number of contact points decreases to 4 (2 for each part of the gripper). From the force distributions shown in Fig.6, it can be found that contact becomes much more continuous while relevant output force (torque) has no fluctuation if the revolute joints are fixed. Nevertheless, the required push force increases a lot because of bad alignment of the gripper and work piece as the rotation around the fixed pins can not be adjusted while moving. In this

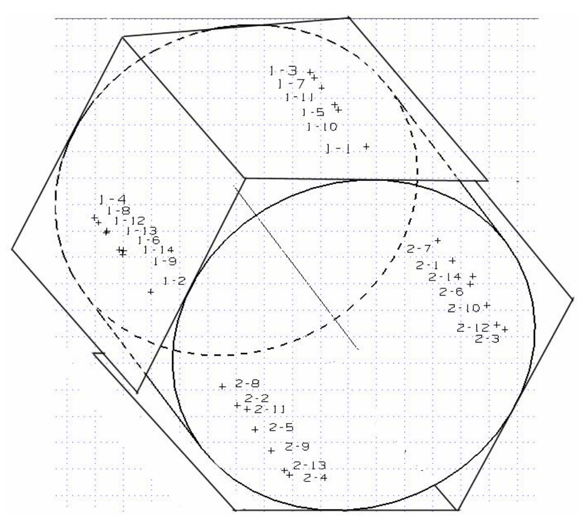

Figure 4. Position of contact points (see from the grippers)
(Note 1-i:upper part;2-i:lower part)

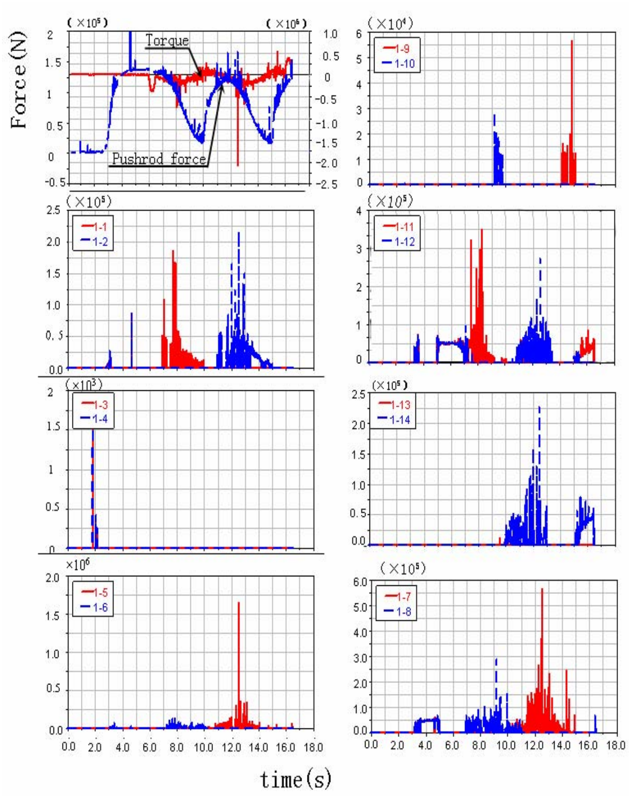

Figure 5. Output force and contact force of upper part of the grippers

case, the specification of driving cylinder and the dimension of the structure should be increased, which would result in higher cost and have disadvantages to the optimization design of the gripper.

According to contact force decomposition, the undulation of contact forces decreases to some extend as the friction at rotating joints of the gripper increases. This is because joint torque can increase press on work piece, resulting in contact friction.

A lot of dynamic simulations show that rotating speed contributes a lot to output torque while rotating. Fig.7 gives the comparison of output torque at different rotating speeds of work piece. It is clear that large undulation of output torque appears at the rotating speed of 5rpm. Output torque undulation reduces as rotating speed increases gradually. A smooth curve of output torque is obtained when rotating speed increases to 20rpm.

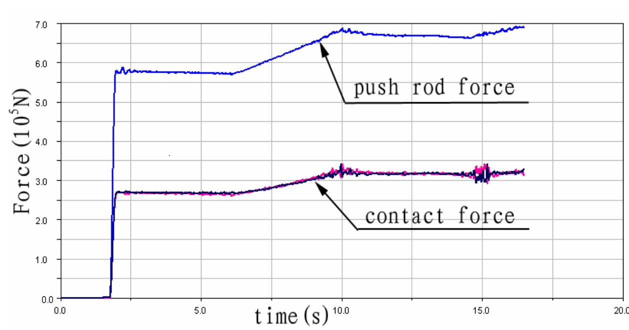

Figure 6. Forces in case of fixed grippers

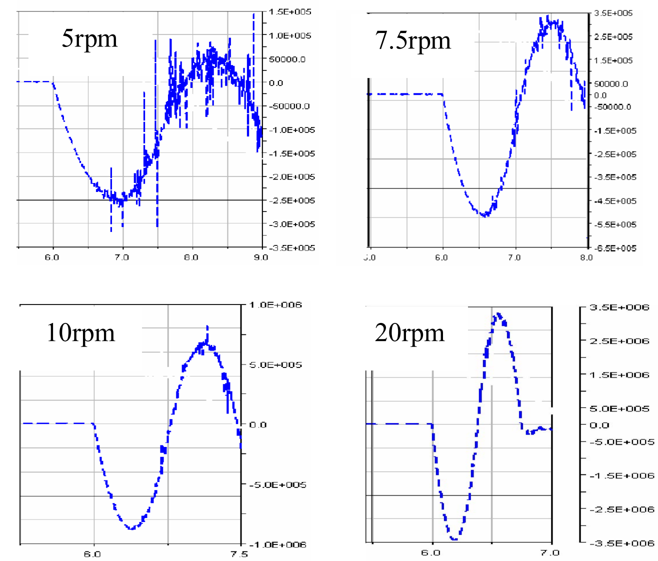

Figure 7. output torque at different rotating speeds

V. CONCLUSION

The issue of stable gripping is studied in terms of the contact forces between the gripper and work piece calculated by space decomposition. It is found that the rotation of the gripper around the fixed pins is the main cause of the contact force undulation that affects stable gripping a lot and rotating speed has a significant effect on the contact force undulation. To improve the gripping stability, the friction between grippers and their rotation pins should be increased properly. The above analyses provide a good foundation for the optimization design of the gripper structure and the control system design of forging manipulators.

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