Analysis and Comparison of Contact Forces between the Constrained Tongs and the Under-constrained Tongs

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**Abstract.** A comparison of contact forces between the constrained gripper and the under-constrained gripper to grip the same work-piece is analyzed. The new type heavy forging grippers with constrained rods are designed to improve the contact status. The main difference between the new grippers with constrained tongs and the traditional grippers with under-constrained tongs is that the constrained gripper has constrained rods to keep the two tongs parallel. A gripping model has been presented in which the gripping operation is equivalent to the grasp of multi-fingered robot hands with friction contact point model. The models for calculating contact forces with constrained tongs and under-constrained tongs are presented with different constraint functions based on gradient flow optimization algorithms, and the constraint functions describe the definite state of the tongs during forging operation. By comparing the simulation and experiment results of the contact and gripping forces, it shows that the contact forces are different when the gripping in different rotation angles and the contact forces with constrained tongs is much smaller than that with under-constrained tongs, especially in the vertical position.

**Introduction**

For a large-scale heavy duty forging manipulator, it is very important to keep the gripping stable and reliable during the forging operation. To ensure the safety of forging manipulator and the minimal deflection of the gripped object, and to save energy and reduce geometric sizes, it is necessary to calculate the optimal contact forces for large-scale heavy forging manipulator grippers. Much attention has been paid for the stability of grasping objects. However, there are little researches about how to calculate and optimize the gripping forces for large-scale heavy forging grippers.

The traditional gripper of heavy forging manipulator is a pair of tongs which can be satisfied with the force equilibrium by adjusting the position of contact points automatically, in which each tong has a free joint. An improved mechanism has been designed, four constrained rods are added to the forging grippers, and they can constrain the free rotation of the tongs. Fig.1 (a) is the improved forging grippers with constrained rods, and fig.1 (b) is the forging grippers without constrained rods.

![Fig.1 Mechanical structure of heavy forging grippers](image)

It is helpful for the optimization and design of the heavy forging grippers to compare the contact forces between the constrained tongs and the under-constrained tongs. According to [1], the resultant force of each contact surface when gripping a cylinder can be considered as an equivalent contact force...
force model with friction point contact, and the heavy gripping mechanism has been simplified as a grasp of robot multi fingers including four friction contact points [2]. In this paper, the calculation model of contact forces with under-constrained tongs and constrained tongs are built respectively based on paper [1], and the differences of contact forces between the constrained tongs and the under-constrained tongs are analyzed in detail.

**Force Equilibrium Equations**

As shown in fig.1, it can be known that the constrained gripper is composed of four-bar parallelogram linkage with the arms of the forging grippers. So the tongs of the forging grippers could remain unchanged when gripping objects. The differences between the constrained tongs and the under-constrained tongs are described as follows:

1. The state of constrained tongs is guaranteed by constrained rods which constrain the free movement of tongs, so the tongs are satisfied with force equilibrium all the time in vertical direction.

2. The under-constrained tongs could rotate around the free joint in a small angle. When the contact force closure equations are not satisfied, the tongs can rotate to adjust the contact point positions until reaching new equilibrium with external forces. So the changes of external forces and the direction working on the tongs are the main factors of keeping the state of under-constrained tongs in rotating.

The contact forces between the object and the two ‘V’-shape tongs are a pair of action and reaction forces. Now consider the force closure characteristics of the two tongs, the coordinate system of the upper tongs and the lower tongs is defined as shown in fig.2.

![Fig.2 Contact model of the tongs](image-url)

In addition to the work-piece, the tongs also must meet force equilibrium conditions. Contact points of 1, 2 are simplified as two resultant forces with friction point contact. When the grasp matrix \( G \) in the coordinate system of the tongs and the equivalent forces of all external forces working on the centre of rotation joint are given, the equilibrium equation of tongs can be written with the contact forces from the gripped object [3]:

\[
G_{TU} F_{T1} = W_1. \tag{1}
\]

where \( G_{TU} \in R^{6 \times 3 m} \) is the grasp matrix in the coordinate systems of fig.2 (a), \( m=2 \), \( G_{TU} = [ G_{u1}, \cdots, G_{u2} ] \), \( F_{T1} = [ F_{1}^T, \cdots, F_{i}^T ]^T \) is the contact force wrench of the gripping, \( i=2 \), and \( W_1 \in R^6 \) is a 6D equivalent wrench of all external forces on the upper tong, \( W1=(fx, fy, fz, mx, my, mz )^T \) [3].

Similarly, the equilibrium equation of the lower tongs has the similar form with the upper tong [2]:

\[
G_{TL} F_{T2} = W_2. \tag{2}
\]
where \( G_{TL} \in R^{6 \times 3n} \) is the grasp matrix in the coordinates of fig.2 (b), \( n=2 \), 
\( G_{TL} = [G_{L(i+i)} \ldots G_{L(i+j)}] \), \( F_{TL} = [F^T_{i1}, \ldots, F^T_{ij}]^T \) is the contact force wrench of the gripping, \( j=2 \), and 
\( W_2 \in R^6 \) is a 6D equivalent forces wrench of all external forces on the lower tongs. 

The upper tongs and the lower tongs can rotate around the X-axis, and other movements of the 
tongs are constrained by the mechanical structure. So it is sufficient to calculate the fourth element in 
the external wrench \( W_1 \) or \( W_2 \).

According to [1], the contact forces between the gripper and gripped object can be obtained by 
gradient flow optimization. Therefore Eq.1 and Eq.2 are two constrained equations for 
calculating \( F_{1T}, F_{2T}, F_{3T}, F_{4T}, G_{TL}, G_{TL} \) are easy to be obtained through coordinate transformation of 
contact points in fig.2.

Considering the effect of constrained rods in gripping forged object, the calculation of initial 
contact forces with under-constrained tongs can be distinguished from that with constrained tongs by 
adding the constrained equilibrium equations of tongs to the objective function. And force 
equilibrium equation 1 and 2 of constrained tongs is satisfied all the time by the mechanical action of 
constrained rods, so it is unnecessary to consider the state of constrained tongs. The objective function 
of the constrained tongs can be defined as Eq.3:

\[
\Phi(F, \lambda) = \frac{1}{2} F^T F - \beta^T F + \lambda (G F - W).
\]

However, the objective function of the under-constrained tongs must add two subjected equations 
(1) and (2) [4]:

\[
\begin{cases}
\Phi(F, \lambda) = \frac{1}{2} F^T F - \beta^T F + \lambda (G F - W) \\
\text{s.t.} G_{TL} F_{TL} - W_1 = 0 \\
G_{TL} F_{TL} - W_2 = 0 
\end{cases}
\]

where \( \beta = [\beta^T_1, \ldots, \beta^T_i, \ldots, \beta^T_j] \) is a weighting factor vector and \( \beta_i = [\gamma_i, 0, 0]^T \) with \( \gamma_i \) being a constant. 
\( G \in R^{6 \times 3m} \) is the grasp matrix in coordinate system of gripped object, 
\( F = [F^T_1, F^T_2, \ldots, F^T_j]^T \) is the contact force wrench of the gripping, \( s=4 \), \( G \) and \( F \) can be obtained in the 
paper [1], \( \lambda \) is the Lagrange multiplier. Other parameters are given in Eq.1 and Eq.2.

**Simulation Results and Analysis**

To demonstrate the calculation model, a prototype of forging manipulator is developed. The model 
parameters for calculating the contact forces are based on the experimental prototype. Fig.3 is a 
simplified configuration of the gripper mechanism, and the parameters of the manipulator grippers are 
shown in table 1.

![Fig.3: The simplified mechanism of the gripper](image-url)
Table 1  The parameters of the experimental device

<table>
<thead>
<tr>
<th>b[m]</th>
<th>b1[m]</th>
<th>b2[m]</th>
<th>b3[m]</th>
<th>b4[m]</th>
<th>θ[°]</th>
<th>L[m]</th>
</tr>
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<tbody>
<tr>
<td>0.34</td>
<td>0.269</td>
<td>0.422</td>
<td>0.22</td>
<td>0.58</td>
<td>164</td>
<td>0.28</td>
</tr>
</tbody>
</table>

The gripped object is a steel cylinder whose radius is 0.1m, length is 2.04m and mass is 500kg. The calculation of contact forces is executed in MATLAB, the differences of calculating contact forces between constrained tongs and under-constrained tongs are in calculating initial contact forces of gripping. The calculation of contact forces with under-constrained tongs requires adding decision condition of equilibrium for the tongs to calculation of initial contact forces. And it is unnecessary for the constrained tongs. The final contact forces can be obtained through optimizing the initial contact forces [2, 5].

Fig.4 gives the simulation results of the gripping driving forces. PPjcs and PPjcx are the contact forces of the upper and lower tongs respectively. PPjc is the composition of upper and lower resultant contact forces, PPjc=|PPjcs|+|PPjcx|, and PPower is the driving force.

The maximum gripping forces of the hydraulic cylinder is $3.1\times10^4$N in fig.4 when the tongs are in horizontal direction, and the required minimal driving force is $1.8\times10^4$N in vertical direction for constrained tongs. Conversely, for under-constrained tongs, the maximum driving forces is $8.1\times10^4$N when the tongs are in vertical direction and the required minimal force of that is $3.12\times10^4$N in horizontal position.

Fig.5 is the comparison of the driving forces with constrained tongs and under-constrained tongs.

The simulation results show that the trend of the two curves is completely different when the gripper rotate continuously, and the required maximum driving force decreased by 62 percent. The
required driving force in the horizontal position changes a little, the reason is that the tongs in horizontal direction cannot rotate about the gravity direction of the gripped object. But it is very different in the vertical position. For under-constrained tongs, it is required to increase the driving force to keep the work-piece stable, and for constrained tongs, it is easy to keep stable in a definite direction in which the contact points are in the edge of the tongs, with the result that contact forces decrease rapidly.

An experiment to grip a steel cylinder with 1,9150N was finished in paper [1] on a forging manipulator whose normal gripping capacity is 3,0000N. The experimental results have demonstrate the above characteristics.

Conclusion

The calculation model of contact forces for under-constrained heavy forging grippers is improved by adding constraint function to objective function, and it can distinguish the manipulator grippers with constrained tongs from that with under-constrained tongs. From the result of the simulation, the variation of contact forces for constrained tongs and under-constrained tongs can be obtained during rotation, the contact forces is increased for the former during the first quarter of rotating, and that for the latter is decreased during the first quarter of movement. Because the pair of tongs is symmetrical in mechanism, the fluctuation of contact forces is symmetrical in the whole course of rotation. More importantly, the contact forces for constrained tongs are much less than that of forging grippers with under-constrained tongs. So the effect of constrained rods is very obvious, they decrease the contact forces by constraining the free rotation of the tongs. The forces are the main factors to keep the stable of the gripping object; it is successful in reducing the contact forces to add constrained rods to the tongs.

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