Trajectory Planning for Hydraulic Quadruped Robot and Optimizing of Flow

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Abstract

The advantages of Hydraulic quadruped robot has been widely recognized, The maximum flow, which is outputted by the power system composed of engine and pump, is the key index of the robot. Inspired from the motion behavior of cheetah, planned a new bionic trajectory; With cosimulation by Amesim and Adams analysed the changes in the relationship of the flow of hydraulic oil between bionic trajectory and sinusoidal trajectory, put forward the way of further optimization. Study showed that the trajectory significantly affected the maximum flow of hydraulic oil, bionic trajectory can significantly reduce the peak flow, and reduce the flow fluctuation, a new train of thought was given for the performance optimization of robot.

Keywords

Hydraulic; quadruped robot; bionic; trajectory planning; flow optimization.

1. Introduction

With the high speed, large load capacity, strong maneuverability and strong ability to adapt on the ground, Hydraulic quadruped robot can be used as the mobile platform under the environment without roads to carry out transport task, has huge development potential and broad application prospects in the fields such as military, search and rescue, detection. [1,2]However, building high performance hydraulic robots still faces many challenges, including mechanical structures[3-5], hydraulic sources[2,6,7], control system[8-11], navigation, and environmental identification etc[12, 13]. Among them, the maximum flow rate is an important limiting parameter for hydraulic power system. How to optimize the motion parameters for specific mechanism to improve the motion performance of hydraulic quadruped robot? The relevant research is scarcely ever. In terms of kinematics, trajectory is the important way to optimize robot flow. In this paper, a new bionic foot trajectory is proposed inspired by the characteristics of cheetah's movement behavior. The simulation verifies that this new bionic foot trajectory can significantly reduce the peak flow.

2. Structure configuration and mechanical model of hydraulic quadruped robot

Based on the bionics principle, we designed a virtual prototype of the hydraulic quadruped robot through a series of optimization of the skeleton structure of quadruped mammals, whose mechanical structure is shown in figure 1(a). The robot is 1m long, 0.6m wide, 1m tall when standing stationary, about 70kg. and using the plunger pump driven by on-board fuel engine as the power source. The four legs of the hydraulic quadrangle robot adopt the same mechanical structure and are mounted in the form of the front elbow knee-to-top, which mimics the physiological characteristics of the mammalian front elbow back knee. Each leg has 3 degrees of freedom (Two degrees of freedom of hip joint, respectively, enable the robot to swing the leg in the forward direction and lateral direction; one degree of freedom of the knee joint realize the swing of the lower leg around the knee joint in the forward direction). When the robot is subjected to lateral impact, the lateral swing degree of the hip joint can adjust the posture through the external swing or adduction motion of the thigh, so as to improve the ability of the robot to resist lateral impact.

When the robot is subjected to lateral impact, the side of the hip joint The degree of freedom of pendulum can be adjusted by the lateral movement of the thigh or the adduction movement, thereby improving the robot's ability to resist lateral impact; the degree of freedom of the hip forward and the knee (elbow) joint are in the same plane to jointly realize the robot's forward function . The rotation of all the joints is achieved by controlling the telescopic length and speed of the hydraulic cylinder. The forward swing joint of the hip and the knee (elbow) joint are in the same plane to realize the forward function of the robot. The rotational motion of all the above joints is achieved by controlling the length and speed of the hydraulic cylinder.

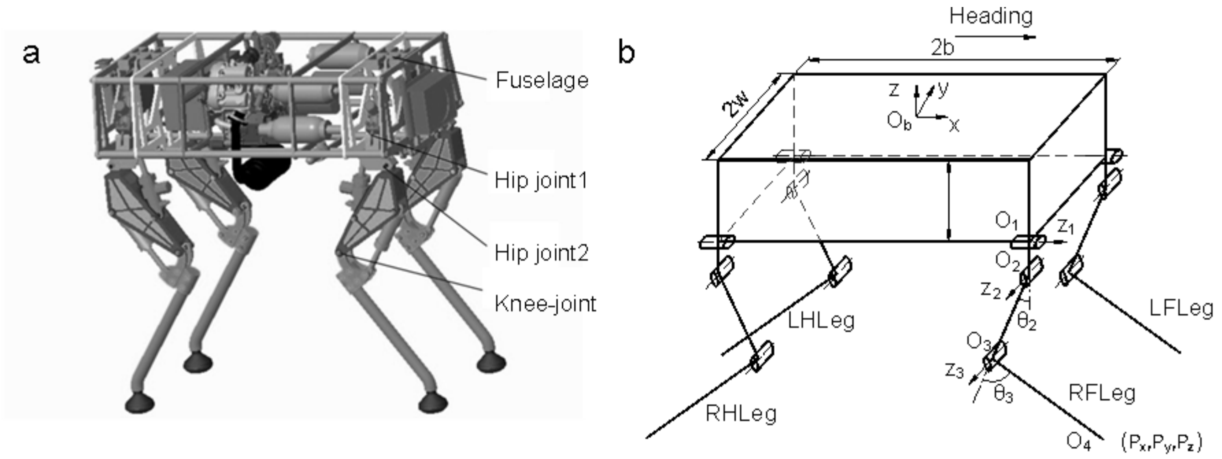

Fig. 1 Virtual prototype and kinematics model of the hydraulic quadruped robot (a) Virtual prototype of the hydraulic quadruped robot (b) Kinematics model of the hydraulic quadruped robot

In order to facilitate the planning of the trajectory of the foot end and the kinematics analysis of the robot, the simplified kinematics model of the quadruped robot is shown in figure 1(b). For convenience of using D-H parameter method[14,15], the four legs are marked as RF (front right) leg, LF (front left) leg, RH (back right) leg and LH (back left) leg as shown in the figure 1(b). $\{O_b\}$ represent the world coordinates of the robot, $\{O_1\}$、$\{O_2\}$、$\{O_3\}$ and $\{O_4\}$ represent the tool frame of the robot, hip joint 1, hip joint 2, knee joint and foot end respectively. (Px,Py,Pz) represents the position and orientation of the of the foot end of the RF (right front) leg relative to the world coordinate $\{O_b\}$. $2b$，$2w$ and h represent the length, width and height of the fuselage. L_2 and L_3 represent the distance of O_2 to O_3 and O_3 to O_4, respectively; a and c represent the vertical and lateral distance from O1 to O2, respectively; θ_1、θ_2 and θ_3 represent the angular displacement of hip joint 1, hip joint 2 and knee joint, respectively. Based on the above definition and related parameters, the inverse kinematic solution of the robot's right foreleg described in this paper can be deduced as follows:

$$\theta_1 = \arcsin\left(\frac{-c}{\sqrt{X^2+Y^2}}\right) - \arctan(X/Y) \tag{1}$$

Where, $X = P_y + w - c$,$Y = P_z + h$,

$$\theta_2 = \arccos\frac{L_3 s_3 B + (L_2 + L_3 c_3)A}{L_2{}^2 + L_3{}^2 + 2L_2 L_3 c_3} \tag{2}$$

$$\theta_3 = \arccos\frac{A^2 + B^2 - L_2{}^2 - L_3{}^2}{2L_2 L_3} \tag{3}$$

Where, $A = Py\sin(\theta_1) - Pz\cos(\theta_1) - a - h\cos(\theta_1) - c\sin(\theta_1) + w\sin(\theta_1)$, $B = P_x - b$, $s_3 = \sin(\theta_3)$, $c_3 = \cos(\theta_3)$, The inverse kinematic solution of the other three legs is similar.

In practical hydraulic quadruped robot, due to the limitation of mechanical structure, each joint can only rotate within a certain range, and the movement space of which is closely related to the working space of the foot. In addition, the working space of the foot end is also the basis for determining the step length, leg height and other related parameters in the trajectory planning. This paper mainly studies the trajectory planning and flow analysis of the diagonal gait of the robot in a flat terrain environment. Therefore, the lateral swing motion of hip joint 1 can be ignored, so the one-leg model of the quadruped robot can be simplified to a two-dimensional plane for discussion. The working space of the robot's RF leg can be obtained by taking hip joint 2 as the origin of coordinates, as shown in figure 2.

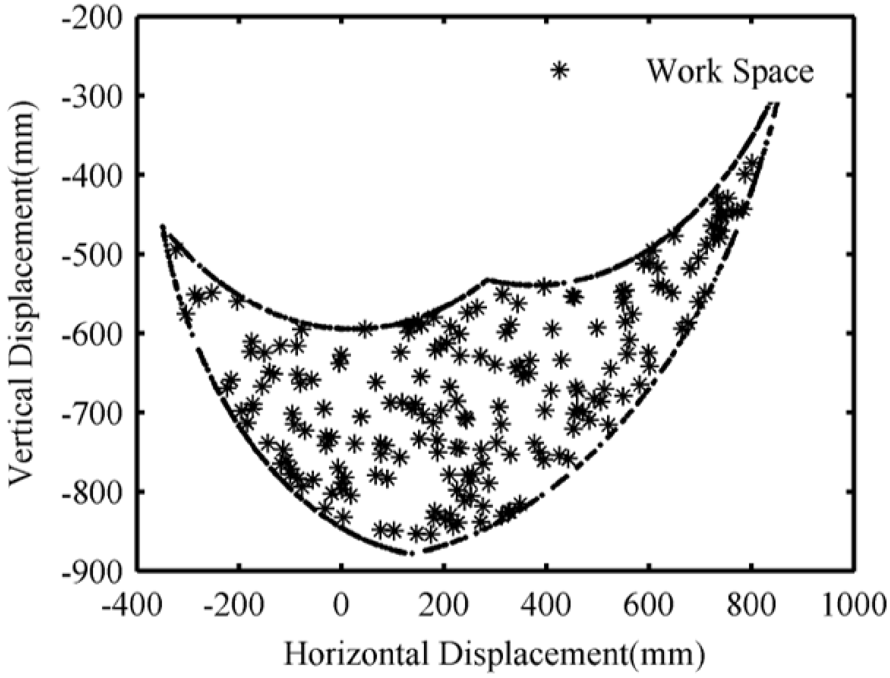

Fig.2 Work space of RF leg of quadruped robot

3. Bionic Trajectory Planning

Through the previous kinematic analysis, we obtained the corresponding relationship between joint space and foot end working space, and further deduced the corresponding relationship between hydraulic cylinder displacement and joint angular displacement with the help of cosine formula. Detailed parameters and calculation process are shown in the literature[16].At present, the most typical method of trajectory planning is the sinusoidal trajectory proposed by Sakakibara.Y in 1990[17], which has been widely used [18,19].The track expression is generally written as:

When $0 \le t \le T_y$

$$x = S\left(\frac{t}{T_y} - \frac{1}{2\pi}\sin\frac{2\pi t}{T_y}\right) - \frac{S}{2} \tag{4}$$

$$\begin{cases} z = 2H\left(\frac{t}{T_y} - \frac{1}{4\pi}\sin\frac{4\pi t}{T_y}\right) & 0 \le t \le \frac{T_y}{2} \\ z = 2H\left[\frac{T_y - t}{T_y} - \frac{1}{4\pi}\sin\frac{4\pi(T_y - t)}{T_y}\right] & \frac{T_y}{2} \le t \le T_y \end{cases} \tag{5}$$

When $T_y \le t \le T$

$$x = \frac{S}{2} - S\left[\frac{t - T_y}{T - T_y} - \frac{1}{2\pi}\sin\frac{2\pi(t - T_y)}{T - T_y}\right] \tag{6}$$

$$z = 0 \tag{7}$$

Where, x and z are the coordinate in the tool frame {O_4}, S and H are the length of the stride length and the height of trajectory, T_y is the swing phase time, T is the gait period, t is the time. So the robot's foot trajectory can be determined by S, H, T and Ty. According to this method, the planned trajectory of the foot can theoretically ensure that the velocity and acceleration of the foot of the robot are zero when it touches the ground, thus reducing the impact of the robot. However, the initial object of this trajectory was not hydraulic robot, and Sakakibara.Y did not take flow optimization into account. Calculation also proved that the flow peak of the hydraulic robot was larger when it walked according to this trajectory. In this paper, based on the principles of bionics and the basic requirements of trajectory planning, key points were extracted from the foot trajectories of cheetah's diagonal gait in proportion, and a bionic trajectory was designed by polynomial fitting method. Its expression is as follows:

When $0 \le t \le \frac{T}{5}$

$$x = 1250S(\frac{t}{T})^4 - 758.33S(\frac{t}{T})^3 + 140S(\frac{t}{T})^2 - 2S\frac{t}{T} - \frac{S}{2} \tag{8}$$

$$z = -250H(\frac{t}{T})^3 + 75H(\frac{t}{T})^2 \tag{9}$$

When $\frac{T}{5} \le t \le \frac{3T}{8}$

$$x = -351.19S(\frac{t}{T})^4 + 387.38S(\frac{t}{T})^3 - 163.15S(\frac{t}{T})^2 + 33.01S\frac{t}{T} - 1.98S \tag{10}$$

$$z = -1596H(\frac{t}{T})^4 + 1891.4H(\frac{t}{T})^3 - 826.79H(\frac{t}{T})^2 + 154.82H\frac{t}{T} - 9.47H \tag{11}$$

When $\frac{3T}{8} \le t \le \frac{T}{2}$

$$x = -49821.15S(\frac{t}{T})^5 + 108738.87S(\frac{t}{T})^4 - 94220.44S(\frac{t}{T})^3 + 40498.79S(\frac{t}{T})^2 - 8635.79S\frac{t}{T} + 731.98S \tag{12}$$

$$z = -25798.53H(\frac{t}{T})^5 + 53950.69H(\frac{t}{T})^4 - 44576.16H(\frac{t}{T})^3 + 18186.37H(\frac{t}{T})^2 - 3667.55H\frac{t}{T} + 293.49H \tag{13}$$

When $T_y \le t \le T$

$$x = -2S\frac{t}{T} + 1.5S \tag{14}$$

$$z = 0 \tag{15}$$

The meaning of the related letters in (8)-(15) is the same as in (4)-(7). For the convenience of comparison, S、T and H are set to the same values for sinusoidal trajectory and bionic foot-end trajectory. According to the actual structure and working space of the hydraulic quadruped robot, S=150 mm，H=100mm，T=0.25s were selected as examples to analyze the flow rate of the robot when walking along sinusoidal and bionic tracks. The shape of the trajectory obtained by the two different planning methods under the above parameters and its displacement-time, velocity-time relationship in the horizontal and vertical directions are shown in Figure3 and Figure 4, respectively. The swing phase and support phase of the two trajectory are continuous in the forward direction and the displacement and velocity of the vertical direction, and at the moment of transition from the swing phase to the support phase (when t=T/2) the speed of the foot end is zero both in the vertical direction and forward direction, thus reducing the impact and friction of the robot foot end facing the ground.

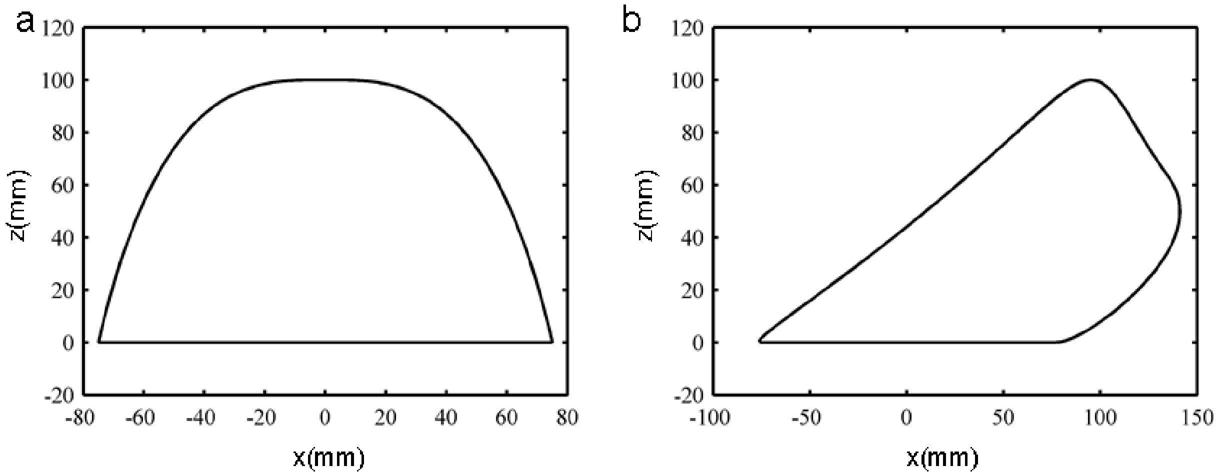

Fig.3 Geometrical shape of sinusoidal trajectory and bionic trajectory (a) Geometrical shape of sinusoidal trajectory (b) Geometrical shape of bionic trajectory

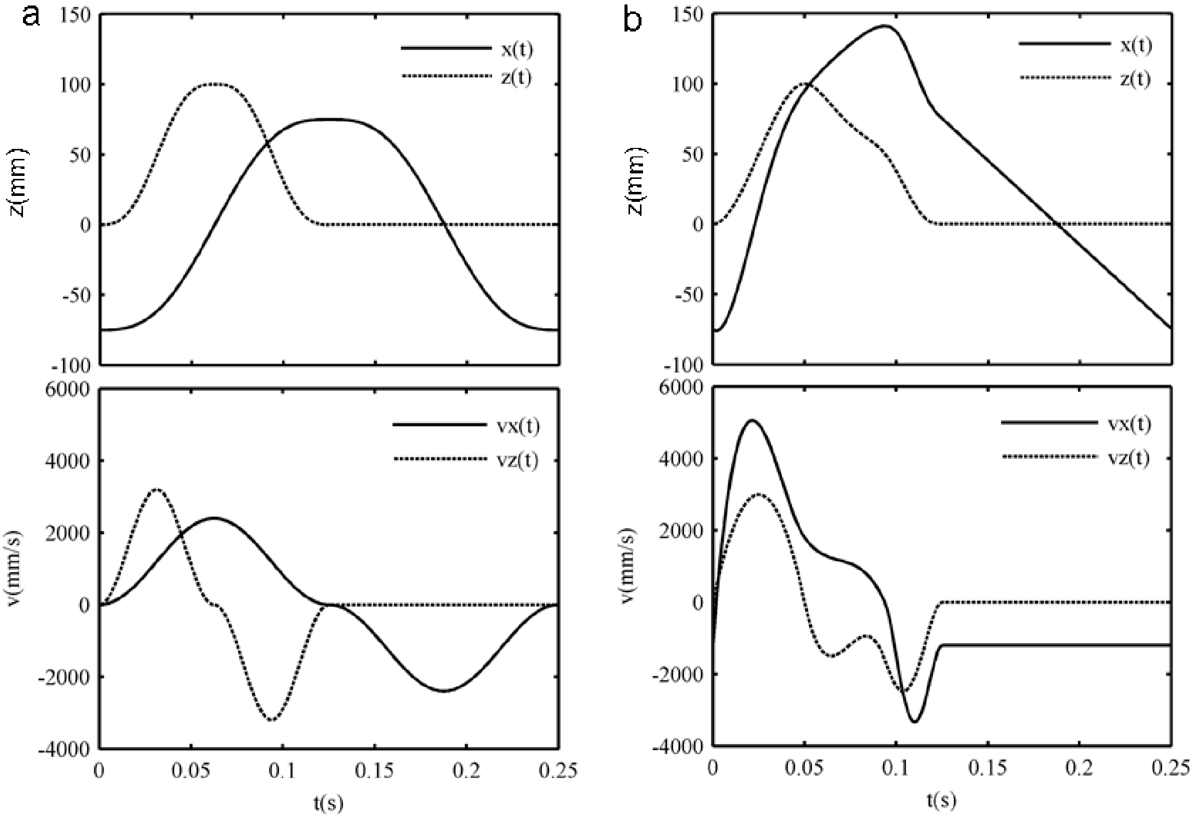

Fig.4 The relationship of displacement - time, speed - time of sinusoidal trajectory and bionic trajectory (a) The relationship of displacement - time of sinusoidal trajectory (b) The relationship of speed - time of bionic trajectory

4. The influence of foot-end trajectory of the system flow

In order to analyze the influence of foot trajectory on the flow of hydraulic quadruped robot and optimize the system flow peak, it is necessary to study the flow of robot when walking according to different foot trajectory. For the determined foot-end trajectory, the displacement change of the hydraulic cylinders of each joint can be obtained by using the cosine formula, by the formula (1) - (3) and the mechanical structure of the legs, the maximum flow of the system can be calculated, but the calculation is a lot of work. In view of the fact that mechatronic-hydraulic joint simulation technology is relatively perfect at present[20]. In this paper, Adams and Amesim joint simulation (see references for the construction of joint simulation platform[21]) was used to analyze the flow rate of hydraulic quadruped robot. The system flow rate of the quadruped robot adopt sinusoidal trajectory and bionic trajectory was studied and the simulation results are shown in figure 5. The required maximum flow is 150L/min when the hydraulic quadruped robot walks along sinusoidal trajectory, while 85L/min when walking according to the bionic trajectory, In addition, the fluctuation of system flow is smaller when the robot walks along the bionic trajectory than the sinusoidal trajectory.

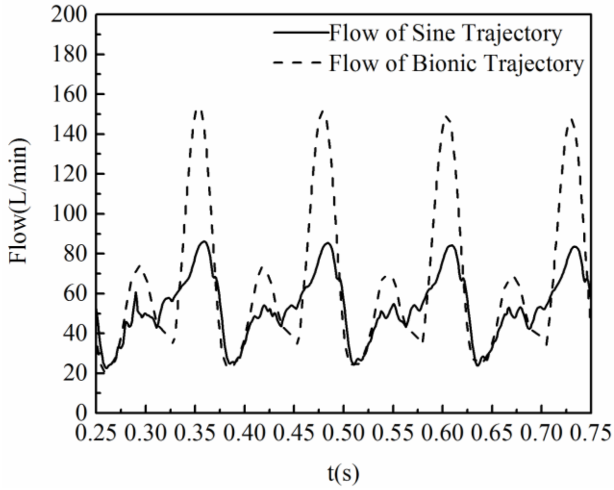

Fig.5 The influence of foot trajectory of the system flow

In order to analyze the reasons why the bionic trajectory can reduce the system flow, the movement of the hydraulic cylinder under the two kinds of trajectory is further analyzed. We can select the right front leg and the left rear leg for analysis since the two groups of legs on the diagonal of the robot have the same movement rule. The results of the analysis are shown in Figure 6.

It can be seen from the displace-time relationship of the hydraulic cylinder of the robot leg that when the hydraulic robot walks on the bionic trajectory, the displacement of the hydraulic cylinder especially the one on the thigh is smaller than that when it walks on the sinusoidal trajectory. Therefore, the bionic trajectory reduces the invalid displacement of the hydraulic cylinder at the same forward speed. The relationship between speed and time of hydraulic cylinder shows that when the hydraulic quadruped robot walks on the bionic trajectory, the maximum speed of all hydraulic cylinders on both the right front leg and the left rear leg is significantly decreased compared with the sinusoidal trajectory. The flow-time relationship of hydraulic cylinder shows that the bionic trajectory can not only reduce the system flow, but also reduce the fluctuation of system flow. On the one hand, this is due to the fact that the maximum flow rate reduce of each hydraulic cylinder when the robot walks according to the bionic trajectory; On the other hand, the trajectory of the bionic foot makes the legs of the robot in the swing phase stagger the peak flow of each hydraulic cylinder.

To sum up, the influence of foot trajectory on the flow of hydraulic robot system is mainly reflected in two aspects: reducing the invalid stroke of hydraulic cylinder and reasonably distributing the speed of each hydraulic cylinder. The geometry of trajectory affects the travel of each hydraulic cylinder of the robot. The smaller the total travel of hydraulic cylinders, the smaller the total flow of the robot system in one cycle. The speed of the foot end affects the instantaneous flow. When planning trajectory, on the one hand, the speed of each hydraulic cylinder should be reduced as far as possible; on the other hand, simultaneous peak speeds of hydraulic cylinders should be avoided as far as possible.

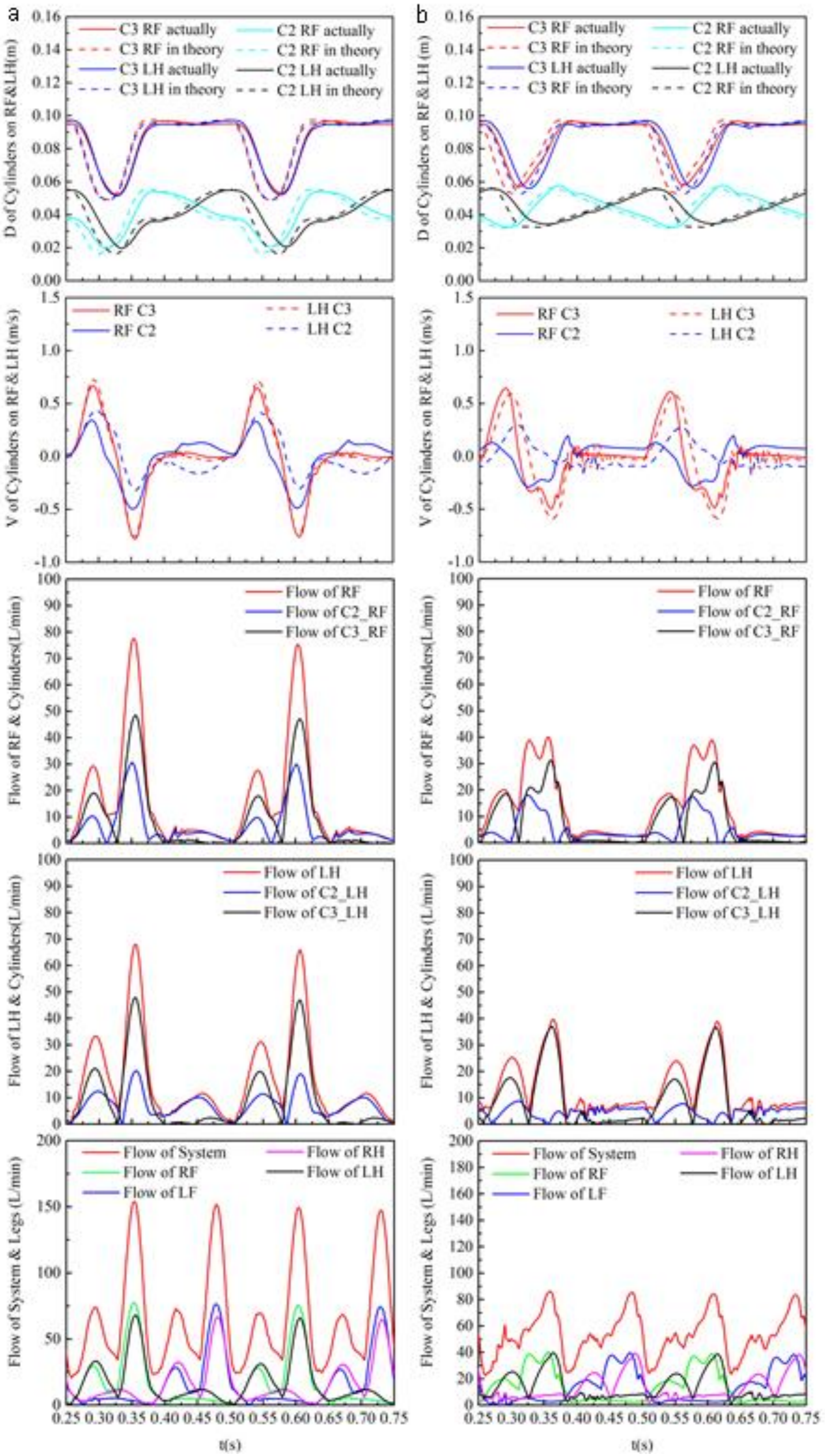

Fig.6 Impact on flow from trajectory (a) Impact on flow from trajectory of sinusoidal trajectory (b) Impact on flow from trajectory of bionic trajectory

5. Conclusion

Flow is an important index of hydraulic robot, and flow optimization is a technical challenge in the robot design process for a long time. Inspired by the movement behavior of cheetah, we planned a novel bionic trajectory, compared and studied the flow rate of hydraulic cylinders in the system and legs when the hydraulic quadruped robot walks in sinusoidal and bionic trajectory by co-simulation of Adams and Amesim, based on hydraulic quadruped robot prototype. the results show that the bionic trajectory, compared with sinusoidal trajectory can significantly reduce the system flow fluctuation and the peak flow of hydraulic quadruped robot. It provided an effective and feasible new path to optimize the hydraulic quadruped robot system flow rate and improve the performance of the robot.

Acknowledgements

Research was supported by the Scientific Research Project of Education Department, Hunan Province (Grant Number: 17C0299).

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