Design and analysis of a single adjustable damping force robotic leg working with magnetorheological technology

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Abstract. Aiming at the problems of leg’s huge impact faced by legged robot in running movements, an adjustable damping force robotic leg working with magnetorheological technology was designed. The mechanism of how the magnetorheological damper adjusts the damping force of the robotic leg is analyzed. Based on SLIP model, the dynamic of the robotic leg was established. With Foot contact force, the displacement of the hip joint in the vertical direction and the loss of leg’s energy as the optimization objectives, the optimal damping force at different velocity was obtained by weight optimization algorithm, and the curve of the optimal damping force of the leg varying with the speed of the body is fitted. The cushioning capacity of the leg was simulated and verified at a speed of 4 meters per second, and the results showed that the structure with adjustable damping force meet the requirements of high cushion performance in running movements.

1. Introduction

Compared with traditional wheeled and crawler robots, legged robots are more adaptable and passable on unstructured ground such as sand and rock shallows, over- distance ditches, rugged mountains, and snow ground. Therefore, the application of legged robots in unstructured ground has broad prospects, such as field rescue, military reconnaissance and interstellar detection, etc [1].

With the research on the application of legged robots in unstructured terrain, people have put forward higher and higher requirements for the speed, mobility, and adaptability of legged robots. At the moment, the high-speed motion of legged robots has also become important study direction. The problems of the robot deviating from the predetermined trajectory, the overall machine instability and structure failure will be caused by the excessive impact between the foot with the ground when the legged robot move at high speed [2]. As the important basic motion component, the legged robot’s leg have a significant influence on the motion performance of the legged robot during running movements [3]. Many animals have excellent high-speed movement capabilities. Observations and experiments on a large number of animal movements have shown that a leg composed of bones, muscles, and tendons can be approximated by a spring-loaded inverted pendulum (SLIP) model with damps [4]. This model
is applied to the design of the robot’s leg. Spring and damper are considered in the design to simulate animal legs to slow down the impact of the foot and the ground during running movements [5].

Many legged robots were designed based on SLIP model. Because the hydraulic system can cushion and has strong driving ability, hydraulic transmission type is used in some quadruped robots such as Big Dog [6], HyQ2Max [7], etc. But the problems of the parameters of calf size change with time, unstable calf stiffness coefficient and insufficient toes control are prone to appear on hydraulically driven legs. Haoyu Ren [8] and Sprowitz [9] arranged a linear spring between the thigh and heel of the robot to absorb the impact energy. It has achieved certain results, but it was too weak to adapt to different situations. The foot of StarLETH [10] is equipped with modular springs emulating the behaviour of the Achilles tendon and Soleus muscle to intermittently store energy during contact phase. But the structure placed on the calf increased leg inertia. It’s not conducive to high-speed movement. Inspired by biology, CARL [11] equipped a compliant foot with flexible materials to absorb and relieve ground impact, but it is prone to uncontrollable leg stiffness and weak terrain adaptability. These all reduce the impact on the legs of the high-speed lower-footed robot to a certain extent, but because the stiffness and damping cannot be actively changed or the frequency of the change is limited by the driver, the best effect is not achieved. Magnetorheological fluid (MRF) is a smart material that can quickly change the damping force only by changing the situation of the magnetic field [12]. Moreover, the magnetorheological damper (MRD) designed based on MRF can quickly change the damping force by altering the coils input current or voltage to adjust magnetic field [13].

This paper designs a bow-shaped leg and applies the magnetorheological damper to the design of the robot leg. At the moment, the mechanism of MRD adjusting damper force is analysed. Taking foot contact force, hip joint up-and-down displacement and leg energy loss as optimization targets during running, weight optimization method is used to analyze the optimal spring stiffness parameters and speed and leg damping force control curves. Combined with Adams dynamic simulation software, the leg structure is simulated and verified under running movements.

2. Design of changeable damping force MRD leg

2.1 Design of changeable damping force leg

Arched legs have better performance in running movements. This arched leg is composed of hip, thigh, calf, Achilles tendon, metatarsal rob, and toe. Considering the design principle of low inertia leg, the motor driving the thigh and calf are coaxially arranged at the hip joint. The thigh drive motor is directly
connected to the thigh, and the calf is driven by a connecting rod. Based on the principle of lightweight design, the MRD is integrated into the thigh as a part of the thigh. Inspired by bionics, the Achilles tendon is flexibly modified using springs. In this way, the spring and MRD constitute a variable damping force system. A rubber toe is installed at the end of the metatarsal rod to increase the friction between the toe and the ground to improve movement performance. The structure of the MRD leg is shown in Figure 1. Where $l_{CD}$, $l_{FH}$ and $l_{DF}$ are the length of thigh, calf and metatarsal rob; $l_{CD}$ is the length of the rob to drive calf; $l_{BD}$ is the distance point B to point D.; and their respective values are given in Table 1.

Table 1. Main parameters of the leg

| Parameters | Value(mm) |
|------------|-----------|
| $l_{CD}$   | 229       |
| $l_{BD}$   | 60        |
| $l_{CD}$   | 40        |
| $l_{DF}$   | 169       |
| $l_{FH}$   | 134       |

2.2 Structure of MRD

The structure of MRD is shown in Figure 2. The main component is a cylinder body made of electrical pure iron, which is mainly used for supporting, bearing internal pressure and magnetic permeability. The front end cover, the back end cover and the sealing ring form a sealing system. To prevent
magnetic flux leakage, the front and rear covers are made of aluminium. The piston rod is made of electrical pure iron. In order to increase the effective strength, a two-section coil design is adopted.

![Figure 2. Structure of MRD](image)

2.3 Work principle

The spring at the Achilles tendon and the MRD together form a variable damping force system. When the robot moves at high speed, the reaction force received by the foot causes the metatarsal rod to rotate along the ankle joint and stretch the Achilles tendon spring. At the same time, the piston rod of the MRD is pulled through the wire rope to move. When the piston rod moves, it will receive the damping force from the MRF. In the impact phase, part of the impact received by the foot is converted into the potential energy of the spring and stored, and part of the energy is consumed by the MRD. In the recovery phase, the energy stored by the spring is converted into the kinetic energy of the calf, and the input current of the control MRD is slowly reduced to reducing the damping force of the MRD slowly, preventing the sudden reduction or withdrawal from making the robot uncontrollable. The piston rod returns to the origin under the traction of the spring. The action route of the system of adjustable damping force is shown in Figure 3.

![Figure 3. The force action route](image)
3. Analysis of Damping Force Regulation Mechanism of MRD

Simple control, fast response, and continuously adjustable damping force are the characteristics of MRD. The basic working modes of MRD are mainly divided into valve type, shear type, extrusion type and shear valve type. Among them, the shear valve type has both the advantages of the valve type and the shear type, and the structure is simple, and it is the most widely used. This paper also uses shear valve MRD as an adjustable damping force device. The diagram of shear valve MRD is shown in Figure 4.

![Figure 4. The diagram of MRD](image)

The coils wrapped around the piston core generate a magnetic field under the action of electric current. The magnetic field lines emerge from the piston core, vertically pass through the damping channel, along the iron cylinder, and then vertically pass through the damping channel again, and finally return to the piston core to form a closed circuit. The MRF in the damping channel produces magnetorheological effects under the action of the magnetic field. When the piston rod moves linearly, the MRF at the bottom is squeezed, $F_s$, and the squeezed MRF flows out along the damping channel. At this time, shear and viscous forces are generated to prevent the piston rod from moving. According to the classic rheological theory, a simplified calculation model of the damping force $F_v$ of the shear valve MRD can be derived, namely the Bingham plate model, and the calculation formula is as follows:

$$F_v = F_\eta + F_\tau = \frac{12\eta L A_p^2}{\pi D h} v + \frac{3L \tau A_p}{h} \text{sgn} v$$

(1)
Where $F_\eta$ means the viscosity. $F_\tau$ represents the Coulomb force. $\eta$ means the zero-field viscosity of the MRF. $L$ means the effective length of the piston. $A_p$ means the surface area of the piston. $h$ means the width of the damping passage between the piston and the cylinder. $D$ means the outer diameter of the piston. $v$ means the movement speed of the piston relative to the cylinder.

In the actual situation, the value of $F_\eta$ is much smaller than the value of $F_\tau$, which is ignored for the convenience of calculation. But the friction $f$ between the piston rod and the sealing ring cannot be ignored. Therefore, the formula for calculating the damping force $F_c^*$ of the sorted MRD is:

$$F_c^* = F_c + f$$

Therefore, the damping force can be changed by the current.

4. Analysis of Stiffness and Damping Force of the leg

For the running robot to maintain the optimal state of motion at all times, it is necessary to adjust the damping force of the legs according to different motion speeds. For the motion analysis of the leg of the legged robot, it can be simplified to a slip model with damping force, shown in Figure 5.

![Figure 5. SLIP model with damping force](image)

In the SLIP model, the position of the foot relative to the body at the moment of landing has a great influence on subsequent support. When the landing point is in the right position, the forward speed of the highest point of the two cycles of flight remains unchanged, and this position is the midpoint [5]. The movement process when the landing point is the midpoint is shown in Figure 6.

Based on the robot running at a constant speed and steadily, landing point is selected as the midpoint. The dynamic model of the landing phase is a multi-dimensional linear equation, which is difficult to solve. In order to approximate the solution to the ground phase, the model needs to be simplified. In this article, it is assumed that the system is completely passive during the landing process, the entire system has no external force input, and energy is conserved. The kinetic equation is established as follow.
Here \( m \) is the equivalent mass of the leg, \( l \) is the equivalent real-time length of the leg, \( L \) is the length of the leg when the end of the foot touches the ground. \( G \) means gravity. Its value is \( 9.8 \text{ m/s}^2 \). \( k \) is the equivalent of the leg. \( \theta \) is the angle between the leg and gravity.

\[
\begin{align*}
\dot{m}l &= k(L - l) + F_c^* + ml\dot{\theta}^2 - mg \cos \theta \\
\dot{\theta} &= g \sin \theta / l 
\end{align*}
\]

Figure 6. Stand phase of SLIP model

The contact force of the foot \( F_d \), the valve of compression of the leg \( \gamma \), and the energy loss of the leg \( \lambda \) are defined as optimization targets when the hip joint is at its lowest at stand phase. Here \( P_0 \) is the initial total energy of the system. \( P_c \) is the energy consumed by the damping force. The values of \( F_d, \gamma, \lambda \) are calculated as follows:

\[
\begin{align*}
F_d &= k(L - l) + F_c^* \\
\gamma &= \frac{L - l}{L} \\
\lambda &= \frac{P_c}{P_0} 
\end{align*}
\]

The optimal spring stiffness and damping force are calculated by using a multi-objective optimization algorithm at speeds of 2 \( \text{m/s} \), 3 \( \text{m/s} \), 4 \( \text{m/s} \), 5 \( \text{m/s} \), and 6 \( \text{m/s} \) respectively. Min \( f(k, F_c^*) \) is the objective function. \( St \) is a constraint.

\[
\text{Min } f(k, F_c^*) = \{ \lambda(k, F_c^*), \gamma(k, F_c^*), F_d(k, F_c^*) \}
\]
According to the value of each target, the degree of influence on the stability of the fuselage is different, and the linear weighting method is adopted. Each target is assigned different weights, 0.5, 0.3, 0.2, and the single objective function is got as follows:

\[ f^* = 0.5x_1 + 0.3x_2 + 0.2x_3 \]  \[ (9) \]

Among them, \( x_1 \), \( x_2 \), and \( x_3 \) are the normalized values of \( F_d \), \( \gamma \), and \( \lambda \). After optimizing \( k \) and \( F_c^* \) at different speeds, the parameter matrices of \( k \) and \( F_c^* \) are calculated as follows:

\[
\begin{pmatrix}
 k \\
 F_c^*
\end{pmatrix} = \begin{pmatrix}
 k_2 & k_3 & k_4 & k_5 & k_6 \\
 F_c^{*2} & F_c^{*3} & F_c^{*4} & F_c^{*5} & F_c^{*6}
\end{pmatrix} = \begin{pmatrix}
 550 & 580 & 600 & 620 & 630 \\
 10 & 16 & 21 & 30 & 43
\end{pmatrix}
\]  \[ (10) \]

In this article, the stiffness of the leg is set as a fixed value, and the damping force can be actively adjusted. Therefore, 600 N/m was selected as the value of the leg stiffness. Based on the determined stiffness coefficient, from 2 meters to 6 meters, take a point every 0.2 to calculate the damping force at different speeds. The speed-related control function of the damping force is generated by data fitting through the obtained data, and expressed as follows:

\[ F_c^* = -0.1171v^4 + 1.5473v^3 - 7.5230v^2 + 26.8722v - 33.3660 \]  \[ (11) \]

The curve of damping force with velocity is shown in Figure 7.

![Figure 7. Relation between damping force with velocity](image)

5. Simulation and analysis of the leg

This article uses Adams2013 simulation software to simulate the robot's single-leg movement ability. In this simulation, these motors’ position and angular velocity are obtained by solving the inverse
kinematics of the foot trajectory. Then these motors’ position and angular velocity were imported into the STEP function in Adams2013 to control the movement of the leg. The single-leg model of the robot shown in Figure1 was imported into Adams to establish a virtual prototype model, and the dynamics simulation was performed under a running motion of $4 \text{ m/s}$. A movement cycle of a single leg is shown in Figure 8.

![Adams simulation model](image)

**Figure 8.** Adams simulation model

The displacement of the centre of the mass of the hip joint of the leg in the direction of gravity is shown in part (a) in Figure 9. It can be seen that the movement of a single leg has good stability, and the highest and lowest points of each running cycle are almost the same. Part (b) shows the contact force of the leg. The maximum value is around $80 \text{ N}$. It shows that the impact is small. Part (c) and part (d) show the values of the torque of the hip joint and the knee joint during running. Except for individual numerical mutations, the torques of the joints during exercise are very small, and they are all less than $10 \text{ Nm}$. It shows that the structure of variable damping force reduces the influence of the impact on the joint motor very well.
Figure 9. The simulation results of the single leg

Table 2. Comparison with existing robots with the buffering ability

| Robot name          | Compliant | Mass (Kg) | Velocity of running (m/s) | Knee joint torque (Nm) | Contact force (N) |
|---------------------|-----------|-----------|---------------------------|------------------------|-------------------|
| StarlETH (10)       | Yes       | 20        | 0.7                       | 30                     | 280               |
| LCS (8)             | No        | 2         | 0.16                      | 1.5                    | 102               |
| HyQ2Max (7)         | No        | 80        | 1.5                       | 120                    | 500               |
| MIT cheetah (2)     | No        | 23        | 6                         | 42                     | 360               |
| Oncilla Robot (9)   | No        | 4.5       | 0.6                       | 4                      | ×                 |
| CARL (11)           | Yes       | 15.1      | 0.2                       | 80                     | 310               |
| MRD-Leg             | Yes       | **2.9**   | 4                         | **12**                 | **110**           |

Comparisons with other compliant robots or legs are listed in Table 2. The quadruped robot StarlETH, LCS, HyQ2Max, MIT cheetah, Oncilla Robot and the biped robot CARL are listed to compare with MRD-Leg in buffering capacity. The value of knee joint torque and contact force reflect the impact degree. And robot’s mass and velocity of running affect the peak of knee joint torque and contact force.
So compliant, mass, velocity of running, knee joint torque and contact force are listed in Table 2. Compared with other robots in Table 2, the MRD-Leg has a better performance with cushion at high speed.

6. Conclusions

Based on the characteristics of MRD, this paper designs a variable damping force leg of legged robot. The MRD and spring in this leg form the active variable damping structure. The working principle and the structure of the MRD are analyzed. The MRD damping force equation is derived by the Bingham model. Based on the SLIP model, a multi-objective optimization linear weighting optimization algorithm is used to derive the control function of damping force and speed. Finally, a motion simulation of a single leg at a speed of 4m/s was performed through Adams. In the simulation results, the impact force of the leg is about 80N, and the joint torque is less than 10 N*m. The result proves that the design of variable damping force meets the requirement of reducing the impact of the leg.

7. References

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