Design and Analysis of a Hybrid-Driven Ankle Joint for Lower Extremity Exoskeleton Robots

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Abstract. In order to improve the safety and comfort of human-machine interaction and its adaptability to complex unstructured environments, a new type of ankle joint based on series of elastic drive and rigid drive hybrid was designed between the motor and exoskeleton robot. Linear spring groups were introduced to achieve flexible driving and absorb the ground reaction force and other impact vibration. At the same time, a disk brake device was designed to retain the rigid drive function to quickly and accurately respond to the motion of the human ankle joint and reduce human-machine movement deviation. The dynamic model of the ankle joint was established. The stability of the hybrid driver under different parameters were obtained through frequency domain analysis. Through simulation experiments, the accuracy and effectiveness of the model were verified.

Introduction

With the advent of twenty-first Century, the number of patients with cerebrovascular diseases such as stroke has increased dramatically in the world, especially in developed countries. Many countries have increased research and development of exoskeleton robots and developed various prototypes of exoskeleton robots with different functions and capabilities[1], such as BLEEX (Berkeley Lower Extremity Exoskeleton) of Berkeley, HAL(Hybrid Assist Legs) of Japan's Tsukuba University and ReWalk of Israeli company Argo medical Technology[2].

Since Pratt[3] and others of Massachusetts Institute of Technology introduce series elastic actuation to biped walking robots, the application of compliant SEA drive is becoming more and more extensive. Leach designed discretely coupled linear multi-mode driver. Lauria[4] has applied high performance differential series elastic actuator. Haefl[5] applied the clutch and spring parallel actuators to the lower extremities exoskeleton robots. Elliott J. Rouse [6] designed a detachable series elastic actuator for the knee joint prosthesis. In this paper, we designed a new hybrid compliant driver for the ankle joint of a lower limb exoskeleton robot. The compliant drive is realized by introducing a number of linear springs, and the rigid driving is kept by disc brakes, thus the hybrid compliant drive of the lower limb exoskeleton robot is realized.

Design of the Ankle Joint

Hybrid Compliance Driving

Combined with theory of human biomechanics and ankle joint movement analysis, the joint power and torque and the range of ankle joint can be obtained. The gait of lower extremities is periodic, and gait cycle usually refers to time spent on the heel during walking. Each gait cycle can be divided into support stage (Stance Phase) and swing stage (Swing Phase). The supporting stage is the instant from heel touching ground to tip of foot leaving ground, which accounts for about 3/5 of the gait cycle. The swing phase is the instant from tip of foot leaving ground to the moment when heel touches ground, which accounts for about 2/5 of the gait cycle. The movement of ankle joint has three degrees of freedom, which is flexion / extension movement around coronal axis in sagittal plane, adduction / abduction movement around sagittal axis in coronal plane, and internal rotation / external rotation around vertical axis in transverse section. The lower extremity biomechanics experimental data of
Han Yali shows that energy of flexion and extension movement of ankle in sagittal plane is largest compared with the other two degrees of freedom, and rotation angle and motion range are also the largest. Therefore, DC servo motors are used to drive flexion motion of sagittal plane, and the other two degrees of freedom use passive drive.

According to movement principle of the body, when the exoskeleton robot assists in walking, the ankle joint is driven by hybrid compliance actuation in stance phase. This not only have a very good cushioning effect when the robot foot touches the ground, but also fully exerts the functions of energy storage, energy amplification, and energy release of the elastic element, and solve the low output power density problem. In swing stage, active driving of the ankle joint is actuated by rigid connection. In this way, the exoskeleton robot can accurately and quickly respond to the swing of the human ankle joint in the swing stage without ground impact, thereby avoiding the occurrence of human-machine motion deviation. In every gait cycle, the lower extremity exoskeleton robot can not only achieve flexible driving in the supporting stage, but also can realize rigid and fast swing stage rigid driving under the cooperation of the disc brake device. Fig. 1 is a schematic diagram of the hybrid compliant driving principle, which realizes the hybrid compliant driving of the lower extremity exoskeleton robot switching in two driving modes.

Structure Design of Hybrid Compliance Driving

According to the above analysis, a new type of hybrid flexible actuator mounted on the ankle joint of lower extremity exoskeleton robot was designed. Fig. 2 is a structural diagram of the hybrid drive module designed, which is composed of an input drive disk, a tension spring group, a star frame, a disk brake, bracket and an output shaft. The input drive plate is connected to the DC servo motor through the harmonic reducer, and the input drive plate and the star frame are respectively connected to the front and the tail of the six groups of tension and compression springs. The star frame has six swivel arms and is evenly distributed. The disc is fixed in the middle of the star frame. The two disc brakes are fixed on the input drive disc through the bracket. The output shaft is fixedly connected to the star frame but does not contact the input drive plate. When the disc brake is released, the star frame is driven by the restoring force of the tension spring group distributed on both sides of the star frame rotation arm to achieve compliant force and torque output.

![Figure 1. Hybrid compliant driving principle.](image)

**Figure 1. Hybrid compliant driving principle.**

**Figure 2. Structure of the hybrid compliant drive.**

1-Input drive disk  2-tension spring group  3-star frame  
4-braking disk  5-disk brake  6-brake frame  7-output shaft
Dynamic Modelling of the Hybrid Drive

The hybrid flexible actuator has two working modes of compliant driving and rigid driving. Because the dynamic model of rigid driving is relatively simple, and the analysis is also more comprehensive and in-depth, this paper mainly models and analyzes the dynamics of the compliant driving. At present, the biggest problem for compliant driving is that the dynamic model is too simplistic and the stability analysis is lacking. In order to simplify the study of the dynamic model, the mechanical damping characteristics of the drive itself and the moment of inertia of the transmission mechanism are neglected, and even the damping of the elastic element itself is neglected. Prof. Ma Hongwen proposed to add damping elements in elastic element, and analyzed the necessity of adding motor damping, equivalent mass of the transmission mechanism, and converting flexible element of the compliant driver into the spring stiffness and damper in parallel in dynamic model. In order to reduce the model error, based on fully considering the factors such as motor damping, elastic element self-damping, and the equivalent rotational inertia of the transmission mechanism, the dynamic model of the hybrid drive in the compliant drive mode is established, as shown in Fig. 3.

In Figure 3, \( c_m \) represents the equivalent damping generated by the internal rotor of the motor (referred to as motor damping). \( \tau_d \) denotes the desired input torque signal, \( \tau_m \) denotes the torque signal output by the PID controller, \( k_s \) denotes the spring equivalent stiffness, \( q \) denotes the rotational angular velocity of the transmission, \( q_L \) denotes the rotational angular velocity of the exoskeleton ankle, \( c_s \) denotes elasticity. The element damping coefficient, \( J_m \) represents the equivalent moment of inertia of the transmission, \( J_L \) represents the moment of inertia of the exoskeleton ankle, and \( \tau_L \) represents the output force signal. From Fig. 3, we can deduce the system dynamic equation when disc brake is in different states.

\[
\tau_m - \tau_L = c_m \dot{q}_m + J_m \ddot{q}_m
\]

(1)

\[
\tau_L = k_s (q_m - q_L) + c_s (\dot{q}_m - \dot{q}_L)
\]

(2)

where \( q_m, q_l \) are the rotation angle of the transmission mechanism and the rotation angle of the exoskeleton ankle joint. Apply Laplace transform to the above two equations, we get:

\[
T_L = k_s (Q_m - Q_L) + c_s (Q_m s - Q_L s)
\]

(3)

\[
T_m - T_L = c_m Q_m s + J_m Q_m s^2
\]

(4)

where \( Q_m \) and \( Q_L \) are image functions of \( q_m \) and \( q_l \) respectively, and \( T_m \) and \( T_L \) are image functions of \( \tau_m \) and \( \tau_L \) respectively. From (3) and (4), we get:

\[
T_m = k_s (Q_m - Q_L) + c_s (Q_m s - Q_L s) + c_m Q_m s + J_m Q_m s^2
\]

(5)

We use PID controller for feedback control. From fig. 3, we have:

\[
e = \tau_d - \tau_L
\]

(6)

\[
\tau_m = k_p \cdot e + k_i \cdot \int e dt + k_d \cdot \dot{e}
\]

(7)

where \( k_p, k_i, k_d \) are PID proportional, integral, and derivative control parameters.
Apply Laplace transform to equation 7, we get:

\[ T_m = k_p \cdot E + \frac{k_i}{s} \cdot E + k_d \cdot E \cdot s \]

where \( E \) is image function of \( e \). From (1)-(8), the System transfer function is:

\[ G(s) = \frac{T_l}{T_d} = \frac{A_3 s^3 + A_2 s^2 + A_1 s + A_0}{B_3 s^3 + B_2 s^2 + B_2 s + B_0} \]

where:

\[ A_0 = k_s k_i, B_0 = k_s, A_1 = k_p k_s + k_i c_s, B_1 = k_p k_s + k_i c_s + k_s \]
\[ A_2 = k_d k_s + k_p c_s, B_2 = k_d k_s + k_p c_s + c_s + c_m, A_3 = k_d c_s, B_3 = k_d c_s + J_m + J_L \]

**Performance Analysis of the Hybrid Compliant Drive**

Set the parameters of the hybrid compliant drive as follows: spring damping coefficient \( c_s = 8 \times 10^{-4} N \cdot s/m \), \( J_m = 5 \times 10^{-2} kg \cdot m^2 \), \( J_L = 8 \times 10^{-2} kg \cdot m^2 \), \( c_a = 2 \times 10^{-4} N \cdot s/m \), \( k_p = 20 \), \( k_i = 0.001 \), \( k_d = 2 \).

From the polar plot of Fig. 4 in combination with the Nyquist criterion, the Nyquist curve does not enclose the \((-1+j0)\) point, and there is no pole in the right half of \( s \), and the root of the closed-loop system characteristic equation has a negative real part. So this system is stable. When the \( k_s \) parameter changes, the Nyquist curve is on the right side of the imaginary axis and has no intersection with the negative real axis. Corresponding to the logarithmic phase curve of Fig. 5, there is no intersection with the -180 degrees line, so the system has a good amplitude stability margin. However, the intersection point of the Nyquist curve and the unit circle indicates that a resonance peak appears in the amplitude-frequency characteristic curve. By using the logarithmic graph of Figure 9 in conjunction with the Bode criterion, it can be seen that the system's amplitude margin and phase margin are very sufficient, indicating that the system is very stable. But with the increase of \( k_s \), the phase margin shows a decreasing trend, and the \( k_s \) gradually increases and the resonance peak appears and becomes higher and higher, indicating that the stability gradually decreases.

![Figure 4. Nyquist diagram for different \( k_s \).](image)

![Figure 5. Bode diagram with different \( k_s \).](image)

**Conclusion**

In this paper, a hybrid compliant drive for the ankle joint of lower extremity exoskeleton robot is designed. The estimated gait phase is monitored by sensors such as pressure sensor, displacement sensor and encoder, and compliant driving and rigid driving are achieved in different gait phases. We performed dynamic modeling and performance analysis of hybrid flexible actuators, and analyzed the
stability under different parameters. In the follow-up study, experimental prototype will be built on the basis of this article, focusing on study of efficiency of movement, quick follow-up characteristics, and boosting effect compared to conventional drive devices. We will further optimize the design and build more precise walking motion controllers.

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