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Lower Extremity Exoskeleton Control and Stability Analysis Based on Virtual Prototyping Technique

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***Abstract*—The unique human-machine integral system of lower extremity carrying exoskeleton system calls for the similar structure for the human and the exoskeleton, which can simply the stability analysis, but the exoskeleton structure becomes complex. At the same time, the effective lower extremity carrying exoskeleton control method, that is, virtual torque control method demands the exact mass attributes. For the complex mechanism structure, the mathematics model can not be built easily. In this paper, the virtual prototyping software ADAMS is introduced to model the exoskeleton and simulate the kinematics and dynamics, which solve the above problems perfectly.**

Keywords-lower extremity carrying exoskeleton; control; stability analysis; virtual prototyping technique

I. INTRODUCTION

For the lower extreme carrying exoskeleton robot has the complex elements as nonlinear, uncertain and parameters time-varying, the accurate mathematics model is difficult to built, which bring difficult for the system design and affect the control results. Lower extremity exoskeleton intelligent carrying system is a new concept human-machine intelligent robot system. The exoskeleton should shadow the motions of the human and never interfere with these motions[1-4]. For the speciality of this system, the control method for the exoskeleton will be considered independently while not using the study method of the general robot. At present the mostly successful control method is virtual joint torque control, which needs no direct measurements from the pilot or the human-machine interface (e.g. no force or EMG sensors between the two); instead, the controller estimates, based on measurements from the exoskeleton suits only, how to move so the pilot feels very little force. This control scheme is an effective method of generating locomotion when the contact location between the pilot and the exoskeleton is unknown and unpredictable. The control method in paper[4] need the mathematic model of the exoskeleton dynamic equation, while the mass properties can not be gotten exactly.

The similar structure of the human and the exoskeleton can simply the stability analysis for the human center of gravity autonomous adjustment, but the exoskeleton structure becomes complex.

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For the complex mechanism structure, the mathematics model can not be built easily. In this paper, the virtual prototyping software ADAMS is introduced to model the exoskeleton and simulate the kinematics and dynamics, which solve the above problems perfectly.

II. DESCRIPTION OF VIRTUAL JOINT TORQUE CONTROL

Virtual joint torque control selects a generalized force vector such that the control law is constructed in the machine's joint space rather than a set of forces and torques applied at a point on the body. The block diagram of the virtual torque control law is shown in Fig.1. Where G_a represents the system transfer function, which is difficult to get the accuracy model. $G_a^{'}$ is an estimate of the machine forward dynamics. $K(s)$ is the controller.

T_{hm} denote the torque exerted on the plant by human. T_a denote the torque exerted by actuator. T denote all the external torque exerted on the exoskeleton. The human-machine torque can be modeled as:

$$T_{hm} = K_h(q_h - q) \tag{1}$$

K_h is the impedance between the human and the machine, q_h is the human's position, q is the machine's position.

the system dynamics model can be built using Lagrange equation:

$$\vec{T} = \vec{J}(\vec{q})\ddot{\vec{q}} + \vec{B}(\vec{q},\dot{\vec{q}})\dot{\vec{q}} + \vec{G}(\vec{q}) \tag{2}$$

$\vec{J}$ is the inertia matrix and is a function of $\vec{q}$, $\vec{B}$ is the centripetal and Coriolis matrix and is a function of $\vec{q}$ and $\dot{\vec{q}}$, $\vec{G}$ is a vector of gravitational torques, is a function of $\vec{q}$ only.

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The tracking objective of $T_{hm} \to 0$ is identical to the tracking objective $q \to q_h$.

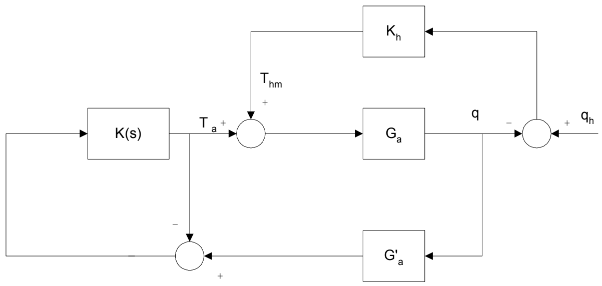

Figure 1. Block diagram of the virtual torque control law

III. VIRTUAL PROTOTYPING MODEL BUILDING AND SIMULATION OF THE EXOSKELETON

The virtual prototyping software ADAMS is used to model and calculate the exoskeleton model G_a in figure 1, which can produce complex mechanical system and simulate the movement process realistically. In Fig.2, the seven rigid body and six freedom exoskeleton simulation model is given. The software SolidWork is used to build the three dimension model, which is imported to ADAMS through the interface between SolidWork and ADAMS. After that, the component attributes and the element attributes are edited, including the appearance, name, oriention, mass, initial speed. The mass and length attribute is shown in table 1.

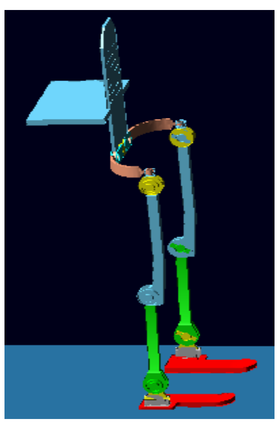

Figure 2. Exoskeleton model built in Adams

TABLE I. MASS AND LENGTH OF LOWER EXTREMITY EXOSKELETON

	trunk	thigh	calf	foot
Length(m)	0.46	0.42	0.34	0.26
Mass (kg)	8.62	7.67	4.59	1.63

The hip joint, knee joint and the ankle joint flexion and extension freedom are connected through rotary components. Adding movement excitation on the components, the joints can move, which can complete the walk course of the exoskeleton. In this paper, the movement is confined to the sagittal plane.

The hip joint, knee joint and the ankle joint torque curves of the swing phase are shown in figure 3 and the Clinical Gait Analysis (CGA) data[5]are shown in figure 4, which show the accuracy of the virtual prototyping model.

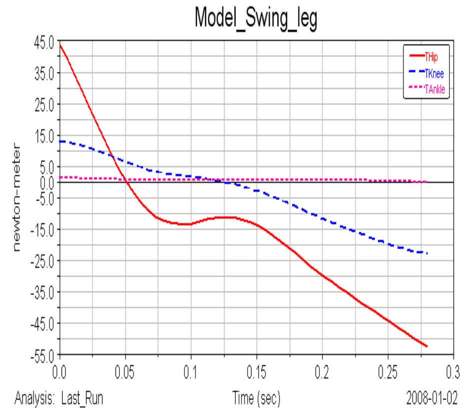

Figure 3. Swing leg joint torque of the virtual prototyping

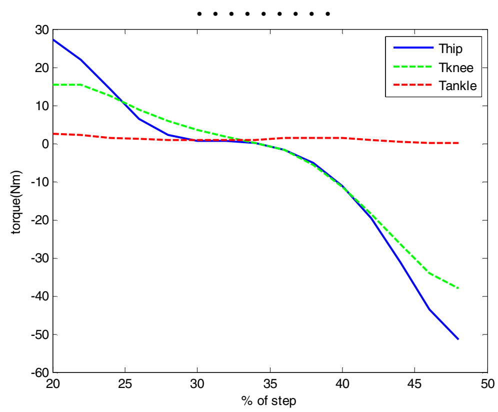

Figure 4. Swing leg joint torque of CGA

IV. DYNAMIC STABILITY ANALYSIS OF THE EXOSKELETON

The popular method of walking robot stability analysis is ZMP(Zero-Moment Point) method. If the exoskeleton can trace the human movement rapidly, the human and the exoskeleton can be taken as an integer, which complete support and walking depending the friction force between exoskeleton and ground and counterforce. Supposing the exoskeleton is a particle, the approximate calculation equation of ZMP is:

$$a_x = x - \frac{z\ddot{x}}{\ddot{z} + g} \tag{3}$$

$$a_y = y - \frac{z\ddot{y}}{\ddot{z} + g} \tag{4}$$

Where x, y, z is the center of gravity position, a_x, a_y is ZMP position. For the exoskeleton is confined to the sagittal plane, only equation (3) can be used to calculate the ZMP position and justify whether it go beyond the ground contact range and whether the system is stable.

Control the exoskeleton to walk from the double support phase to the left leg put up, until the left leg touchdown again, which is shown in figure 5.

The coordinate range of X direction of the heel and the tiptoe of the support foot is $-120mm \sim 130mm$. For the ZMP position of X direction is not beyond the range, the exoskeleton walking is stable.

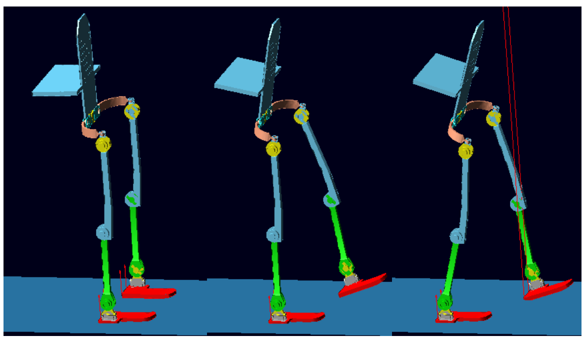

Figure 5. Exoskeleton walking in ADAMS

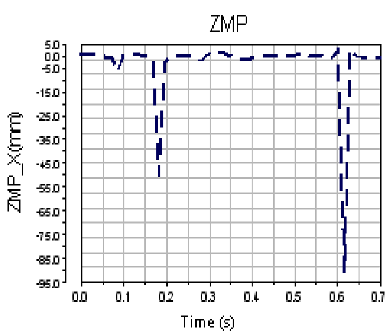

Figure 6. ZMP position of X direction

V. CONTROL OF THE EXOSKELETON

On the following, the validity of using the virtual prototyping model to control in Matlab is shown. Build the single link model in ADAMS, which is shown in figure 7. Using ADAMS/Control module, the export model in figure 8 of ADAMS can be gotten, where S-Function denotes the nonlinear model of ADAMS, State-Space denotes the linear model and Adams_sub includes the nonlinear equation.

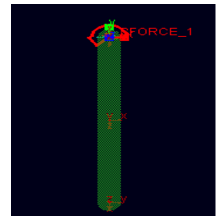

Figure 7. Single link model of exoskeleton

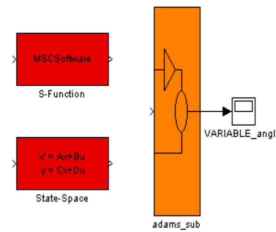

Figure 8. ADAMS export model

Figure 9 is the unite simulation diagram of the ADAMS and Matlab building in simulink.

Set the data exchange time interval to 0.005s and select the solver as variable-step and order45.

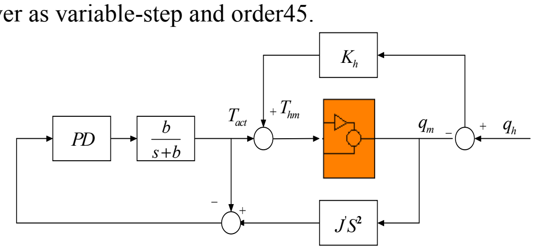

Figure 9. Unite simulation diagram of the ADAMS and Matlab

Select $k_p = 0.1$, $k_d = 0.3$, $K_h = 2$, the unit step angle response simulation results are shown in figure 10 and figure 11. Figure 10 show the torque exerted by the actuator T_{act} and the human T_{hm} on the exoskeleton, figure 11 is the exoskeleton angle output q_m. which illustrate that the exoskeleton tracks the motion of the human very well and the torque exerted by the human is very small and the actuator exert the most which means the pilot (human) can swing the exoskeleton easily and only need to exert a little torque of the actuator.

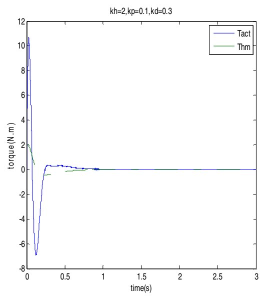

Figure 10. Torque exerted by human and actuator

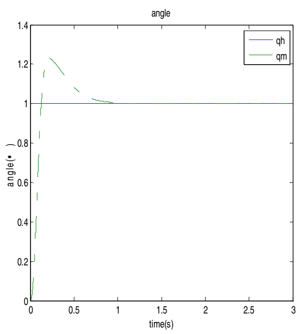

Figure 11. Trajectory of joint angle

VI. CONCLUSION

In this paper, the virtual prototyping software ADAMS is introduced to model the exoskeleton and simulate the kinematics and dynamics, which can building the complex exoskeleton model, improving the stability and control effect of the system, simulation results show the valid of this method.

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