Electro-Mechanical Heterogeneous Simulation of the Complex NC Machine Tool from Gear Milling and Hobbing

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***Abstract*—Electro-mechanical heterogeneous modeling and simulation technique, which is applied to NC machine tool, is one of the difficulties and important approaches to analyze dynamic performances. Based on mathematical model of servo motor with load, the horizontal feed system of the complex NC machine tool from gear milling and hobbing was taken as a research object to set up mechanical dynamic model by ADAMS/View and establish control model in MATLAB/Simulation. The electro-mechanical heterogeneous model, which is made up of the mechanical dynamic model and the control model by ADAMS/Controls, was simulated in MATLAB7.0. The simulating results show the validity of the dual closed-loop control project composed of speed loop and position loop. Furthermore, the control moment characteristic of the AC servo motor with load was analyzed, which offers a theoretical basis for drive design as well as electro-mechanical parameter matching of the NC machine tool.**

***Keywords*—electro-mechanical heterogeneous, virtual prototype, complex machine tool**

I. INTRODUCTION

Electro-mechanical heterogeneous (coupling) system is composed of mechanical system, electrical system and coupling electromagnetic field related to the both systems. Traditional design methods only can analyze mechanical system and electrical system separately. If whole performance of the electro-mechanical heterogeneous system needs to be analyzed, physical prototype should be designed and made first. Electro-mechanical heterogeneous modeling and simulation technique can analyze virtual prototype before physical prototype is made and can get whole performance of NC machine tool, which offers a basis for electro-mechanical parameter matching. At present, the most serious difficulty of electro-mechanical heterogeneous modeling and simulation technique is focused on the heterogeneous performance between mechanism and electron, namely semantic differences in different fields and data format differences induced by adopting different software in the same field [1].

Theoretical analyses and modeling methods of electro-mechanical heterogeneous system, which is based on simplified mathematical model, is in virtue of setting up dynamic differential equations of the system by means of some known theorems and laws. This modeling method is easy to understand and is applied to simple electro-mechanical systems [2]. Nevertheless, electro-mechanical system of NC machine tool is complex and non-linear, so it cannot reflect the facts by mathematical modeling.

In the near years, along with the development of the computer technology, the origin and application of automatic modeling and simulation software make it possible to analyze complex heterogeneous systems, for example:

(1) 20-Sim, made by University of Twente, Netherlands, can realize modeling and simulation of the electro-mechanical and hydraulic hybrid system. However, it's too abstract and professional.

(2) MATLAB, made by Mathworks, America, can model multi-body system directly and realize heterogeneous modeling and simulation by means of Simulink module together.

(3) SimulationX [3], made by ITI, Germany, is multidisciplinary and universal for modeling and simulating electro-mechanical heterogeneous systems. There is a powerful and standard element base in it, by connecting these elements heterogeneous model can be founded.

(4) ADAMS, made by MSC.Software, can set up dynamic model of any complex system. ADAMS/Controls, which is a plug-in module of ADAMS, can add control system to the corresponding mechanical module constructed in ADAMS.

Comparing with the other electro-mechanical heterogeneous simulation software, ADAMS and MATLAB have outstanding advantages in course of designing NC machine tool. In ADAMS, it is possible to make parameterized dynamic model of multi-body system for any complex electro-mechanical system. Using this model, kinematical and dynamic characteristic can be analyzed, the results of which can be return to CAD and CAE software to optimize structural parameters of the machine tool.

MATLAB is a large piece of software for designing control system, in which a variety of advanced control systems can be dealt with. In this paper, the horizontal feed system of the complex NC machine-tool from milling and hobbing, which was developed by our graduate school, was taken as the research object to realize electro-mechanical heterogeneous modeling and simulation by ADAMS2005 and MATLAB7.0. The simulating results can be used to analyze dynamic performances of the electro-mechanical heterogeneous system, the technical line of which is illustrated as Fig. 1. Synthetically using Matlab/simulink module in electrical field and ADAMS/Control module in mechanical field, i.e. adding the control system to the mechanical model, the electro-mechanical heterogeneous servo system can be simulated in MATLAB7.0, and then the electro-mechanical heterogeneous integration model of the complex NC machine-tool from milling and hobbing can be established. The control system of which can be certain by adjusting PID parameters. The electro-mechanical heterogeneous servo system can be analyzed based on the virtual prototype, the results of which offer theoretical bases for designing electro-mechanical parameters. During the mutual connection of models, the designers can intervene in creating the mechanical and control models at any moment, which makes modification and reconstruction of the models become easy.

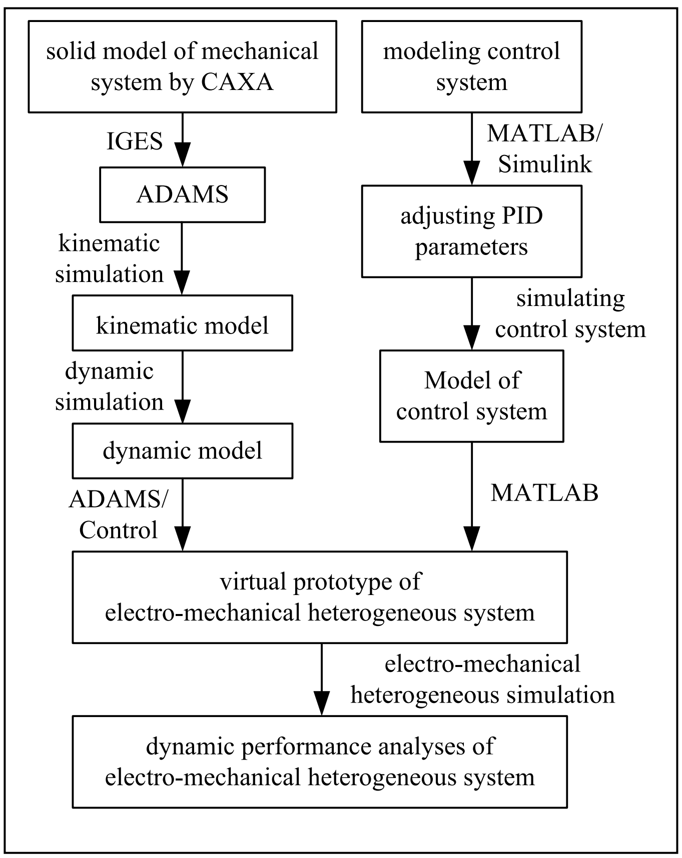


Figure 1. Technical line of modeling and simulating electro-mechanical heterogeneous system

II. ELECTRO-MECHANICAL HETEROGENEOUS MODELING OF THE COMPLEX NC MACHINE TOOL FROM MILLING AND HOBBING [4,5,6]

Virtual prototype is an all-around and multi-subject CAE technology developed rapidly along with the developing of the computer technology in 1980s. During the process of the product design, the models of the machine tool can be built on computer to simulate and forecast dynamic performance.

CAXA, which adopts fast and easy drag-and-drop operation, intelligent catch and three-dimension sphere orientation techniques, can model any complex geometric entity efficiently. Moreover, CAXA uses particular double-geometry core technology (ACIS, Parasolid) and provides a variety of standard data interfaces. The solid model of the complex NC machine tool from milling and hobbing, which was made in CAXA, is given in Fig. 2.

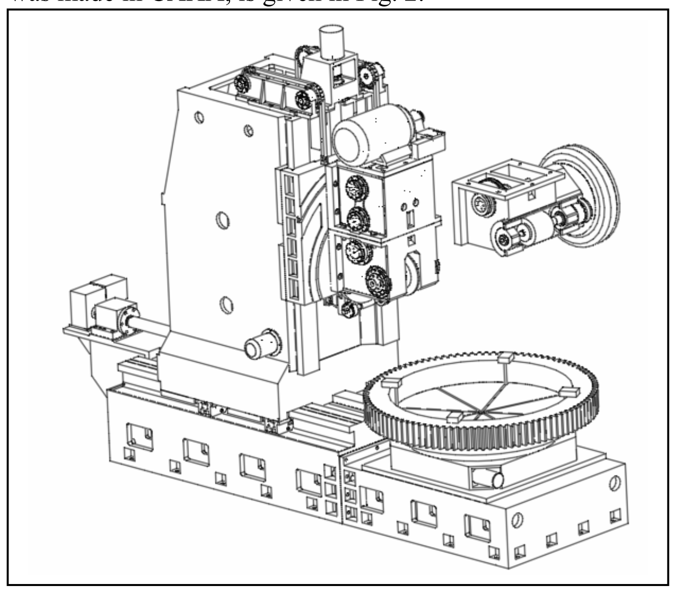
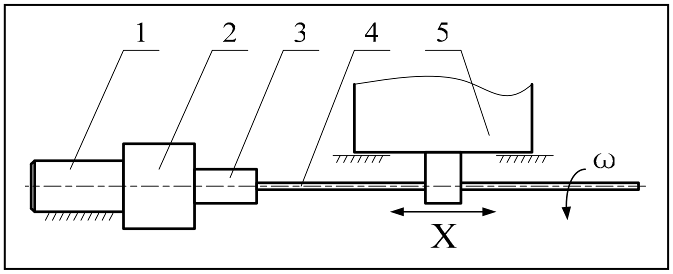


Figure 2. Solid model of the complex NC machine tool from gear milling and hobbing

The complex machine tool can realize complex functions by replacing headstock, the complex movements of which involve one main drive and three feed drives. Horizontal and vertical feeds associated with circular feed of the rotary table are controlled simultaneously by control system to realize contour milling and generating hobbing for large diameter and module gears.

In this paper, the horizontal feed system of the complex NC machine tool from milling and hobbing was taken as example to research electro-mechanical heterogeneous modeling and simulation technique. The horizontal feed system adopts screw drive type, the moving sketch map of which is illustrated as Fig. 3.



1-AC servo motor 2-planetary reduction gear 3-coupling
4-ball screw shaft 5-column

Figure 3. Moving sketch map of the horizontal feed system

AC servo motor, the rotate speed of which is controlled by vector changing of magnetic field, can be equal to DC servo motor. In rotary orthogonal coordinates system, the mathematical model of AC servo motor is same with DC servo motor. In this paper, DC servo motor was taken as the example to describe the mathematical model of the horizontal feed system, the sketch map if which is illustrated as Fig. 4.

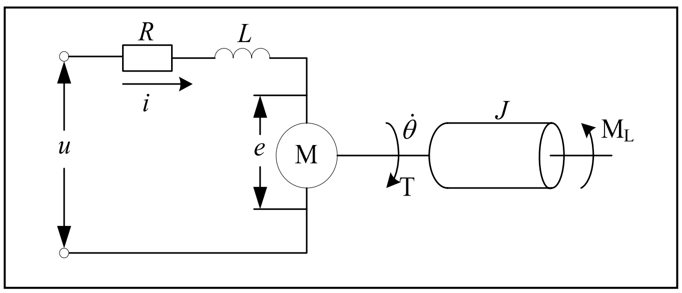


Figure 4. Schematic diagram of the horizontal feed system

Supposing the motor is rigidly coupled with the loads and the damp of the system is ignored, the corresponding electro-mechanical coupled relation will be described as Fig.5.

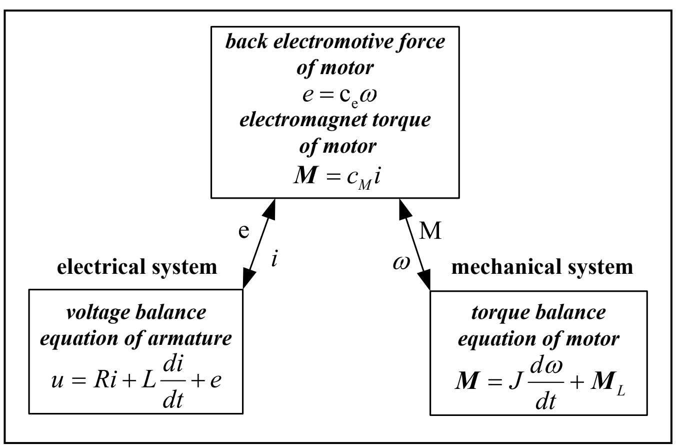


Figure 5. Relation chart of electromechanical coupling system for DC motor

Based on Kirchhoff's law, force law acted by a coil carrying current in magnetic field, law of electromagnetic induction and Newton second law etc, electro-mechanical heterogeneous mathematical model of the horizontal feed system was constructed after cleaning it up [7].

$$LJ\dddot{\theta}(t) + RJ\ddot{\theta}(t) + K_M K_e \dot{\theta}(t) + RM_L = K_M u \quad (1)$$

In (1):

L — Self inductance of armature-circuit,

R — Resistance of armature-circuit,

u — Armature voltage,

K_M — Moment coefficient of motor,

K_e — Back EMF coefficient of motor,

J — Moment of inertia sum of electric machine rotor and its dragging mechanical system,

M_L — Load torque.

A. ADAMS Model Establishment of Mechanical System

Some simple mechanical structure can be modeled in CAXA directly, but modeling complex structure needs CAD software, e.g. UG、PRO/E、CAXA etc. In this paper, the mechanical model of the horizontal feed system was built in CAXA2006. Then transmit it to ADAMS/View by standard data interface IGES and the dynamic model of which is illustrated as Fig. 6.

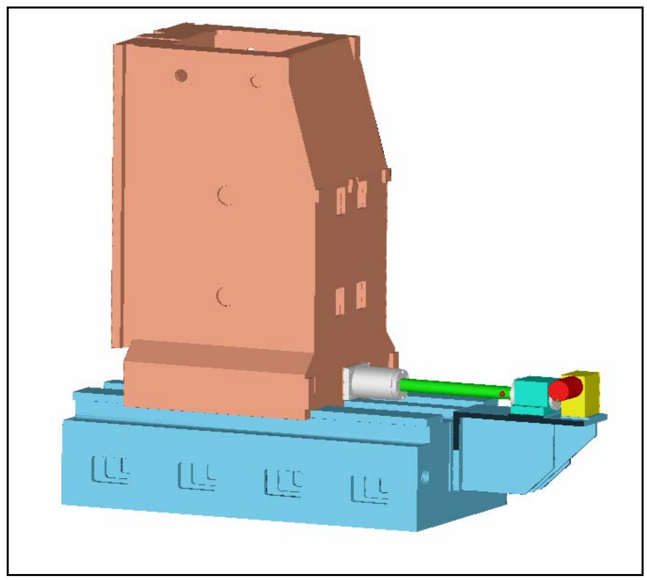


Figure 6. ADAMS Mechanical Model of the horizontal feed system

Kinematical pairs of the model were added in ADAMS/View [8]. Bed was joined with ground by fixed pair; planetary reduction gear and bearing pedestal were joined with bed by fixed pair; motor and ball screw shaft were joined with ground by rotary and coupling pairs, the transmission gear ratio of the reduction gear was set as 29.5:1; screw shaft was joined with screw pedestal by rotary pair, the lead of the screw was set as 20 millimeters; screw pedestal was joined with column by fixed pair; column was joined with bed by moving pair, coefficient of static friction was set as 0.2, coefficient of kinetic friction was set as 0.1. Finally, rotary drive was added to motor. DOF of the system was zero, so it can meet the demands of kinematical simulation.

Driving force and driving moment were added to the kinematics simulation model to establish dynamic simulation model of the system. For analyzing it easily, the accessories of the column were omitted, such as headstock, additional weight and vertical base plate etc. The weight of the accessories, which can be added to the column, is totaled about 24 tons. Considering the effect of the control moment upon accelerating the horizontal feed system, horizontal moving speed was set as 2 meters per minute and starting time of the motor was set as 0.1 seconds.

$$F = ma = 24\times10^3 \times (2/60)/0.1 = 8\times10^3 (N) \quad (2)$$

$$M = (Fh)/2\pi = (8\times10^3 \times 0.02)/2\pi = 25.5(Nm) \quad (3)$$

Considering acceleration of the horizontal AC servo motor as linear, torque generated by acceleration is about 25.5 Nm. But in practice, because of opposite clearance of driving, there exist impacts against motor while start-up or changing direction. The load torque of the AC servo motor generated by acceleration was set as 125Nm and loaded to the ball screw shaft.

Furthermore, milling is heavy cutting, so a kind of clamp device was fixed to the column avoiding impacts against the horizontal feed system. While designing drive system, influence on cutting force can be ignored.

B. Definition of Input and Output Variables in ADAMS

Fig. 7 shows interface between ADAMS and MATLAB, in which a closed loop occurs. Outputs of ADAMS become inputs of control system and outputs of MATLAB become inputs of mechanical system.

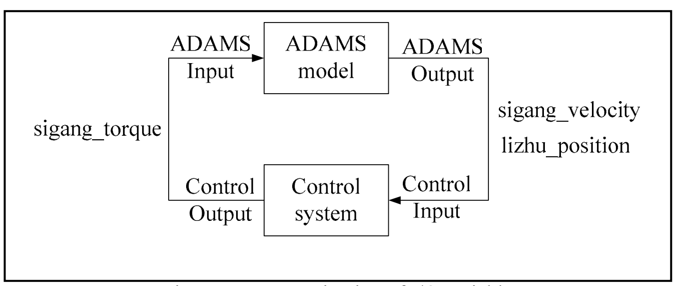


Figure 7. Determination of I/O variables

The added rotary drive on the motor was cancelled, torque of ball screw shaft (*sigang_torque*) was defined as an input variable, rotary speed of ball screw shaft (*sigang_velocity*) and displacement of column (*lizhu_position*) were define as output variables.

C. Foundation of the Control System Model [9,10]

The control model of the horizontal feed servo system was erected in MATLAB/SIMULINK. Together with the dynamics model erected by ADAMS, a closed loop model of the electro-mechanical heterogeneous system was established in MATLAB. Generally speaking, the servo system of the NC machine tool is composed of three loops, i.e. current loop, velocity loop and position loop. But manufacturers determine current loop in most cases, so users cannot modify it. In this paper, a double close loop control system, which consists of velocity loop and position loop, was adopted to analyze performances of the electro-mechanical heterogeneous servo system. The velocity loop is the inner loop, feeding back velocity parameter of the ball screw shaft, while the position loop is the outer loop, feeding back position parameter of the column to control system.

Function of the velocity loop is to improve the anti-interference capability and restrain the fluctuation of velocity. Function of the position loop is to ensure static precision and dynamic tracking performance of the system. In engineering practice, velocity loop adopts PI adjuster and position loop adopts P adjuster. In that case, if limiting frequency of the position loop is far less than the reciprocal of any time constant of the velocity loop, closed-loop transfer function of the velocity loop will be the equal of a first-order inertia unit, which can reflect the characteristics of the velocity loop factually in theory and practice. It also can predigest the design of the position loop, by which stability of the servo system is easy to analyze.

Parameters of the control system were adjusted as follows: beginning with the inner loop, the inner adjuster was designed at first. Then regard it as a member of the outer loop to design adjuster of the outer loop. Until all the adjusters were adjusted successfully, the electro-mechanical heterogeneous system could be simulated. Scale coefficient of the position loop, scale coefficient and Integral time constant of the position loop were adjusted in MATLAB and the control flow chart is illustrated as Fig. 8.

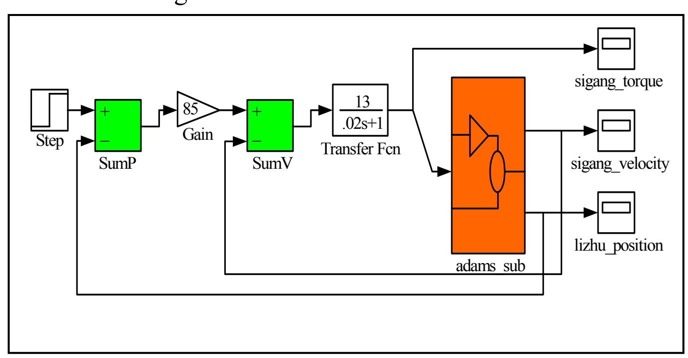
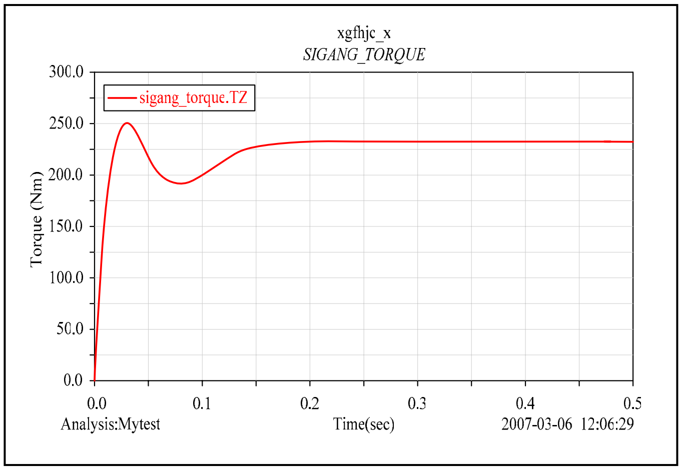


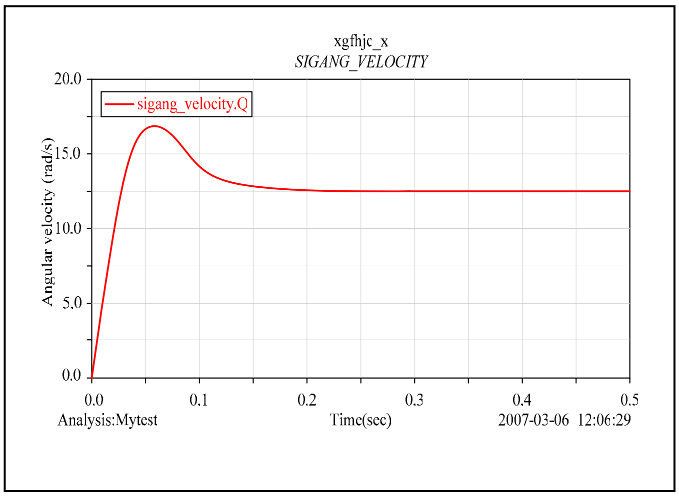
Figure 8. Control flow chart of the electro-mechanical heterogeneous system

III. Electro-Mechanical Heterogeneous Simulation of the Complex NC Machine Tool from Milling and Hobbing [11,12]

The unit step function was taken as the signal source to simulate the electro-mechanical heterogeneous system in MATLAB7.0, the simulating results of which are illustrated as Fig. 9.



(a) Control torque of the ball screw shaft



(b) Angular velocity of the ball screw shaft

(c) Displacement of the column

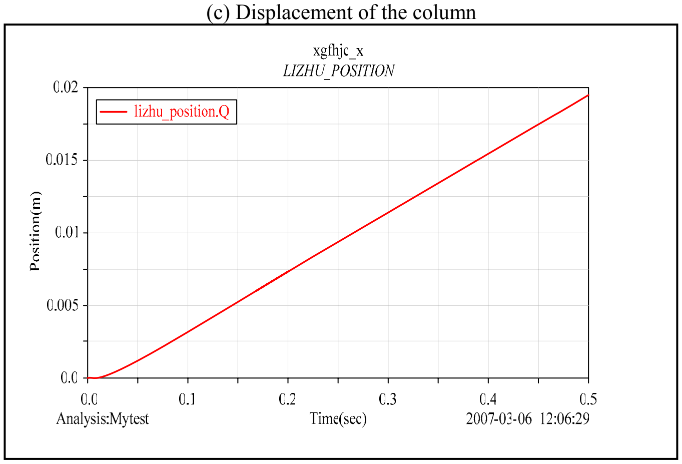


Figure 9. Results of simulating the electro-mechanical heterogeneous system

Due to Response curve of Fig. 9, we know that start-up time of the motor is about 0.2 seconds, steady value of control torque on the ball screw shaft is 230 Nm, and steady value of angular velocity is 12.5 radians per second. The simulating dynamic performance of the system is given in TABLE I. Obviously, the overshoot of angular velocity is too large, but in practical application, the cutting width and depth increase by degrees, so cutting force from gear milling and hobbing is not a unit step and actual overshoot of angular velocity is far less than it.

TABLE I. SIMULATING DYNAMIC PERFORMANCE OF THE SYSTEM

Performance index	***Control torque***	***Angular velocity***
Time of regulation (s)	0.2	0.2
Overshoot	8.7%	36%

The simulating results seem that design of the velocity loop and position loop could meet the control demands of the NC machine-tool, which denotes that the double closed-loop control strategy and parameter setting of the horizontal feed servo system are reasonable. It lays the foundation for researching control algorithm of the systems with load; it also provides theory reference for driving design of the NC machine tool.

Considering reduction ratio of the planetary reduction gear, mechanical driving efficiency and safety factor of the system, design torque of the horizontal feed servomotor is calculated as follows.

$$M' = (KM/n)/\eta_G = (2.5 \times 230/29.5)/0.8 = 24.4(Nm) \quad (4)$$

In (4):

K — safety factor of the system,

n — reduction ratio of the planetary reduction gear,

η_G — mechanical driving efficiency.

Therefore, we selected the AC servo motor of SIEMENS, the rated rotate speed is 3000rpm and the rated torque is 27Nm.

IV. CONCLUSIONS

From the results of this research, the following conclusions can be drawn.

(1) Parameters of velocity loop and position loop were adjusted, and then electro-mechanical heterogeneous system of the horizontal feed servo system was simulated in MATLAB7.0. The simulating results show perfect stability, veracity and rapidity of the horizontal feed servo system, it also validates the double closed-loop control strategy.

(2) Comparing with the linear simple mathematical model, virtual prototype of the complex electro-mechanical heterogeneous system established by professional electro-mechanical heterogeneous modeling and simulation software is more close to actual physical prototype. Using ADAMS and MATLAB, the electro-mechanical heterogeneous system of the complex NC machine-tool from milling and hobbing was modeled and simulated, and the analyzing results provide theory reference for matching mechanical and electrical parameters of the virtual prototype and manufacturing the physical prototype.

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