Mechanism and Machine Theory 44 (2009) 1689–1700

Contents lists available at ScienceDirect

Mechanism and Machine Theory

journal homepage: www.elsevier.com/locate/mechmt

Optimum control for an electromechanical integrated toroidal drive

Lizhong Xu *, Xin Liu

Mechanical Engineering Institute, Yanshan University, Qinhuangdao 066004, China

ARTICLE INFO

Article history:
Received 25 May 2007
Received in revised form 14 December 2008
Accepted 4 February 2009
Available online 9 March 2009

Keywords:
Toroidal drive
Electromechanical integrated
Optimum control
System equation
Speed track

ABSTRACT

In this study, the system equations for the electromechanical integrated toroidal drive are presented. Based on it, the system equations considering speed fluctuations is given as well. An optimum control strategy is used to remove the speed fluctuations and realize desired speed tracks. The optimum state feedback control scheme is obtained and the optimum control signals are also presented. The effects of the mechanical and electrical parameters on the optimum speed track system of an electromechanical integrated toroidal drive system are investigated and the optimum parameters for the control system are selected. Small speed track errors are achieved and the speed fluctuation of the drive system is eliminated.

1. Introduction

Toroidal drive can transmit large torque in a small size. They are suitable for applications in aviation and space flight fields [1–5]. As more electrical and control techniques are utilized in mechanical engineering fields, generalized composite drives will find new applications in advanced mechanical science. Electromagnetic harmonic drives [6] and piezoelectric harmonic ones [7] are active drives in which the meshing forces between the flexible gear and the rigid gear are controlled by electromagnetic forces or piezoelectric forces. The drive and power are integrated. The permanent magnet gearing is a passive drive in which the mechanical elements and magnetic ones are integrated [8–10].

Based on recent research [11,12], the authors develop a new electromechanical integrated toroidal drive which integrates control, power and toroidal drive [13,14].

The drive shown in Fig. 1 consists of four basic elements: (1) radially positioned planets; (2) the central worm; (3) a toroidal shaped stator; and (4) a rotor, which forms the central output shaft upon which the planets are mounted. The central worm is fixed. Coils are mounted in helical grooves of its surface. The planets have permanent magnets instead of teeth. The N and S pole permanent magnets are mounted alternately on each planet. The stator has helical permanent magnets instead of helical teeth. In the same manner as the planet, the N and S pole helical permanent magnets are mounted alternately on the stator.

Besides permanent magnets, steel plates can also be used for teeth of the stator. As teeth of the planet are permanent magnets, between planet teeth and steel plate, enough magnetic force can be caused as well. Therefore, under condition that torque transmitted is not quite large, teeth of the stator can be produced with steel plate as well. In model machine as shown in Fig. 1b, teeth of the stator are produced with ordinary steel plate with thickness 3 mm and width 6 mm. Test shows that enough magnetic forces between planet and stator are produced.

* Corresponding author. Tel.: +86 0335 8060195; fax: +86 0335 8074783.
E-mail address: Xlz@ysu.edu.cn (L. Xu).

0094-114X/$ - see front matter
doi:10.1016/j.mechmachtheory.2009.02.001

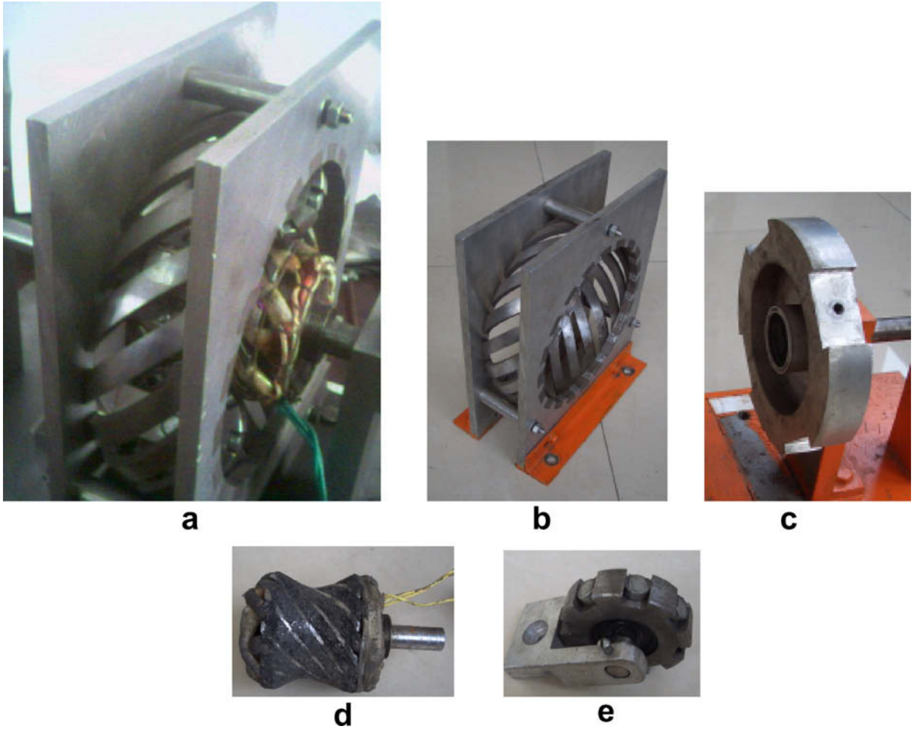

Fig. 1. Electromechanical integrated toroidal drive: (a) model machine, (b) stator, (c) rotor, (d) worm, and (e) planet.

Cylinder or segment permanent magnets can be used for teeth of the planet. The cylinder or segment permanent magnets are mounted on planet body by bonded or other joints. In above model machine, cylinder permanent magnets with diameter 8 mm are mounted on planet body by bonded joints.

The central worm consists of a number of silicon steel sheets. Several helical slots are cut on the worm. The windings made of insulated wire are mounted in these helical slots. In above model machine, the slots with the section size of 8×8 mm^2 are used. Hundred turns of the coils made of wire with diameter 0.5 mm are mounted in each slot.

If a specific relation between planet pitch, tooth number and helical angle on the stator, and number of pole pairs and helical angle on the worm is realized, N pole of one element will correspond to S pole of the other one all along. The attractive forces between N and S pole of the different elements are driving forces and the meshes without contact are realized. When the alternate current is made in the coils of the worm, a toroidal circular field is formed. It drives several planets rotate about their own axial. And by means of magnetic forces between teeth of the planet and stator, the rotor is driven to rotate about its own axial. Thus, a power of low speed and large torque is output.

Compared with simple epicyclic gearing, as the axis of the planet is perpendicular to axes of the worm and stator, and worm and stator are all designed into ring shape, more tooth pairs are in mesh simultaneously. Otherwise, From Fig. 1, it is found that more planets can be mounted between worm and stator. Up to 12 planets can be grouped around the worm, all of which are simultaneously mesh with the worm and the stator to share the load. Therefore, much larger load carrying ability can be given by the drive. Of course, meshes between planets and worm or stator are magnetic meshes without contact.

Moreover, the new drive is easy to produce, is without wear, and does not need lubrication. It is equivalent to one drive system plus one motor. However, the drive system is integrated with the motor, so the drive has very small size. It is suitable for applications in aviation and space flight fields that require compactness. It can also be substituted for a servo system to simplify the structure of an existing electromechanical system, and it can be used with robots and in other fields that require accurate control.

In Ref. [13], authors investigated output torque and the torque fluctuation of the new drive system. In Ref. [14], a typical torque control is presented and the stability and response of the torque control system are investigated. However, in the fields such as robots and so on, the good speed track is required. Therefore, the speed track control of the new drive system should be further investigated.

The output position feedback can solve the problems about robustness and speed fluctuations. However, with the feedback method, it is difficult to optimize the parameters of the controller, its anti-interference ability and the adaptability to the load are not good as well. Therefore, the optimum control strategy should be used.