TORQUE AND SPEED PERFORMANCE STUDY OF DISK TYPE SYNCHRONOUS MAGNETIC COUPLER

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Based on the dynamics of the magnetic coupler under the quadratic load of fluid, the equivalent magnetic charge method is used to solve the output torque magnitudes for different angle differences and air gap thicknesses, and to establish a model of the driven disk dynamics under quadratic load conditions. Finally, analysing the kinetic characteristics of magnetic couplers, and the results show that the output power and angular difference increase with the increase of torque, and the reduction of the active disk starting speed or the increase of the transient starting time are beneficial to the stage operation of the system.

Keywords: mechanical properties; output power; output torque; permanent magnets

1.Introduction

Disc type synchronous magnetic coupler is a non-contact permanent magnet transmission device, which controls the output torque by adjusting the air gap thickness[1] and [2]. At present, most of the magnetic couplers studied by domestic and foreign scholars are eddy current type, and they focus on the calculation method of output torque and the influence of different structural parameters on transmission. However, compared with the synchronous magnetic coupler, the eddy current type magnetic coupler has the characteristics of large eddy current loss, small torque and poor dynamic tracking ability[4] and [5]. Mainly because eddy currents weaken the working magnetic field and reduce the output torque, on the other hand, the resulting eddy current losses are eventually released in the form of heat, which consumes the output power of the magnetic coupler and leads to a reduction in its working efficiency[6] and [7].

However, as mentioned in [8] and [9], scholars' research on synchronous magnetic couplers is mostly limited to the theoretical analysis of output torque and the influence of structural parameters on output torque, and there is a lack of detailed analysis of the motion states of synchronous magnetic couplers at different

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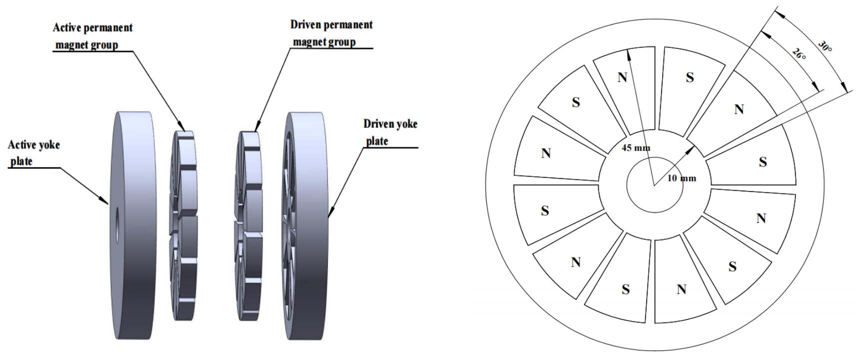
stages and the influence of different operating parameters on motion states. Because the study of the dynamics characteristics of the disk synchronous coupler has not yet formed a complete theoretical system, it still needs in-depth analysis.

In this paper, the disc type synchronous magnetic coupler is subjected to quadratic load, firstly, the output torque is solved by the equivalent magnetic charge method, the kinetic equation of output torque versus speed under quadratic load condition is established. We analyzed the motion regularity of the magnetic coupler on starting phase, acceleration phase and deceleration phase, and the influence of different operating parameters on the kinematic performance of the magnetic coupler is investigated by theoretical analysis and simulation. In a word, these studies will provide theoretical support for the design and development of related products.

2. Magnetic torque equation and motion relationship model

2.1 *Basic Sstructure and rotation mechanism*



(a) (b)

Fig. 1. Permanent magnet arrangement and basic structure of disk type synchronous magnetic coupler. (a) Permanent magnet arrangement. (b) Basic Structure.

The basic structure model of disk type synchronous magnetic coupler is shown in Fig.1(a), including two parts: active disk, driven disk , in which both the active and driven disk are composed of two parts: magnet and yoke, and the active and driven disks do not touch each other, and the torque transmission is realized through the air gap magnetic density interaction, thus avoiding the interference of vibration to the rotation of the driven disk. The magnet is a fan-shaped permanent magnet with uniform magnetization in the axial direction, and the yoke is partially machined with a fan-shaped groove, and the permanent magnets are arranged alternately along the circumferential *N* and *S* poles and assembled in the fan-shaped groove of the yoke, as shown in Fig. 1(b).

The transmission model model of the disk type magnetic coupler is that the motor drives the active disk to rotate, and the magnetic field on the active side and the magnetic field on the driven side are coupled to each other to produce the difference in rotation angle to realize the torque transmission, and the size of the output torque is controlled by adjusting the thickness of the air gap between the two disks, the parameters of magnetic coupler are listed in Table 1.

Table 1

Parameters of magnetic coupler

Parameter	Value
Inner radius of magnet R_1 (m)	0.01
Outer radius of magnet R_2 (m)	0.045
Thickness of magnet h (m)	0.005
Number of pole pairs p	12
Arc angle of magnet θ_1 (deg.)	26
Outer radius of yoke R_3 (m)	0.055
Thickness of yoke h_i (m)	0.015
Slot depth of yoke h_s (m)	0.004
Air gap g (m)	0.003—0.005
Magnet remanence Br (T)	1.23
Magnet relative permeability μ_r	1.0998
Yoke relative permeability μ_1	1.2
Operating temperature (°C)	22

2.2 *Kinetic theory model*

According to [10-12], the relationship between Angle difference and output torque is similar to sine wave, as shown in Fig. 2.

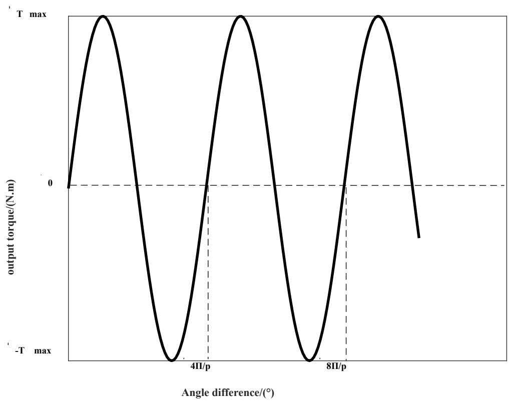


Fig. 2. Relation of Angle difference with output torque

In order to facilitate the analytical derivation and analysis of the equations of motion of the magnetic coupler, The output torque formula is simplified as

$$T = T_{max} \, sin\left(\frac{2\pi}{p}\alpha\right) \tag{1}$$

where T_{max} is the maximum output torque to which the driven disk is subjected,where α is the angle difference between the active disk and the driven disk, p is the number of pairs of permanent magnet poles.
therefore, the kinetic equation of the driven disk can be described as

$$J\frac{d^2\theta}{dt^2}+\beta\frac{d\theta}{dt}=T_{max}\,sin\left(\frac{2\pi}{p}\alpha\right)-T_f \tag{2}$$

where T_f is load torque. J is the moment of inertia of the driven disk.

$$J=\frac{1}{2}m\left(R_2^2-R_1^2\right) \tag{3}$$

where m is the driven disk mass, R_1 and R_2 are the inner and outer radius of the disk respectively. β is the damping factor, at no load β satisfies the following relationship[12]

$$\beta\frac{d\theta}{dt}\le\frac{T_{max}}{10} \tag{4}$$

in this dynamics model, it is assumed that the damping coefficient at no load satisfies the equation

$$\beta\frac{d\theta}{dt}=\frac{T_{max}}{20} \tag{5}$$

assuming that the starting phase is a transient process, the active disk angular velocity equation satisfies

$$\omega_m=\omega_0\left(1-e^{-t/\tau}\right) \tag{6}$$

where ω_0 is the angular velocity when the active disk is stabilized, τ is the motor transient starting time. Then the angle of rotation of the active disk during a period of time is

$$\theta_m=\int_0^t\omega_m dt=\omega_0\left[t-\tau\left(1-e^{-t/\tau}\right)\right] \tag{7}$$

2.3 *Starting phase*

Assume that the rotation angle of the driven disk is θ,the difference in the rotation angle of the active and driven disks is $\alpha=\theta_m-\theta$. Active disk rated speed is 600 r/min, moment of inertia is 1.32446×10^{-3} kg·m^2 by using Eq.(3).

Air gap thickness is taken as 0.003 m, 0.004 m, and 0.005 m respectively. The starting phase is due to the resistance of the fluid machinery in the working process is proportional to the square of the speed, the load torque is $T_f=K_t\omega_f^2$,where K_t is torque constant. ω_f is the angular velocity of the driven disk. Inserting Eq. (2) gives the equation for the start with load of the driven disk as

$$\left(1.32446\times10^{-3}\right)\frac{d^2\theta}{dt^2}+\left(\frac{0.00915}{d\theta/dt}+Kt\frac{d\theta}{dt}\right)\frac{d\theta}{dt}$$
$$=T_{max}\,sin\left\{6\left[\omega_0\left(t-\tau+\tau e^{-t/\tau}\right)-\theta\right]\right\} \tag{8}$$

2.4 *Acceleration phase*

Assume that the initial angular velocity before active disk acceleration is ω_1 and the stable angular velocity after acceleration is ω_2 ($\omega_2 > \omega_1$), then the active disk angular velocity variation relationship is

$$\omega_m = \omega_2 - \left(\omega_2 - \omega_1\right)e^{-t/\tau} \tag{9}$$

initial conditions are $\theta|_{t=0}$ and $\left.\frac{d\theta}{dt}\right|_{t=0} = \omega_1$.

In order to maintain the stability of the system, the sudden change of the angular velocity of the active disk must have a certain time margin to satisfy the mutual coupling of the magnetic fields between the active and driven disks. Assuming that the sudden change of angular velocity of the active disk satisfies the transient process, the equation of motion of the driven disk is

$$\left(1.32446\times10^{-3}\right)\frac{d^2\theta}{dt^2}+\left(\frac{0.00915}{d\theta/dt}+K\frac{d\theta}{dt}\right)\frac{d\theta}{dt}$$
$$=T_{max}\,sin\,6\left\{\left[\omega_2 t - t\left(\omega_2-\omega_1\right)e^{-t/\tau}\right]-\theta\right\} \tag{10}$$

2.5 *Deceleration phase*

Driven disk deceleration is also a process of sudden change of speed. Suppose the steady angular velocity of the active disk before deceleration is ω_3, and stable angular velocity after deceleration is ω_4 ($\omega_3 > \omega_4$). The expression of driven disk deceleration is

$$\left(1.32446\times10^{-3}\right)\frac{d^2\theta}{dt^2}+\left(\frac{0.00915}{d\theta/dt}+K\frac{d\theta}{dt}\right)\frac{d\theta}{dt}$$
$$=T_{max}\,sin\,6\left(\omega_4 t-\theta\right) \tag{11}$$

initial conditions are $\theta|_{t=0}$ and $\left.\frac{d\theta}{dt}\right|_{t=0} = \omega_3$.

Using Ansys Maxwell software to solve the output torque under different Angle differences. The results are given in Table 2, where the air gap thickness is $0.004m$, T_e is the simulation value of the output torque . We can found that: the maximum torque is 11.503 N·m when the turning angle difference is 15° .

Table 2

Relationship between angular difference and output torque

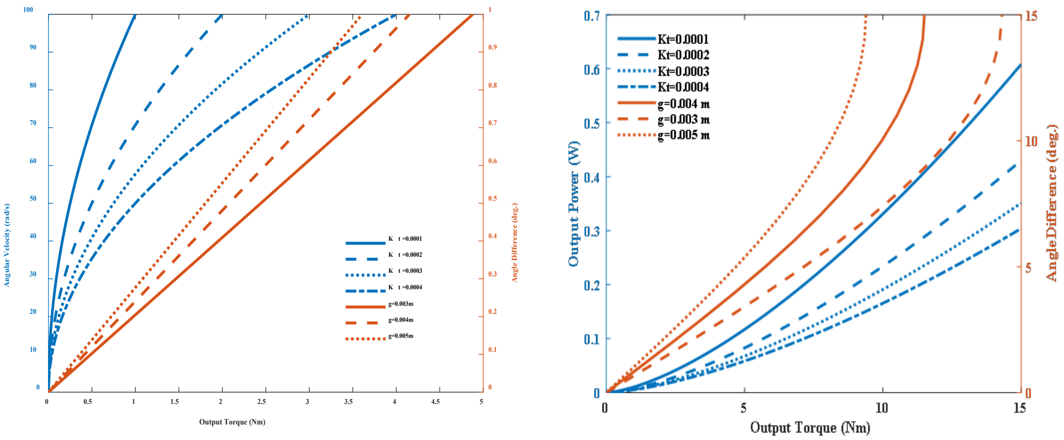
α / (°)	0	5	10	15	20	25	30
T_e/(N.m)	0	6.301	10.227	11.503	10.227	6.301	0

3. Analysis of magnetic coupler dynamics

Mechanical characteristics and power characteristics are two important characteristics that characterize the operation of a disk-type synchronous magnetic coupler. The torque constants taken as 0.0002, 0.0003, and 0.0004, respectively, and analyze the motion characteristics of the driven disk when the air gap thickness is 0.004 m and the rated speed of the active disk is 600 r/min(62.832 rad/s).

As shown in Fig.3, We observed that if the maximum torque is needed, the air gap thickness should be minimized or the angle difference should be increased. Fig.3(a) shows The output torque decreases with the increase of air gap thickness. The angular velocity increases as the torque constant decreases, and the output torque increases gradually with the increase of the angle difference.

As is shown in Fig.3(b), we can found that the smaller the torque constant is, the larger the output power is. When the torque constant is smaller, the output power of the driven disk changes greatly. if the air gap thickness is increased at this time, the output torque will decrease rapidly and decoupling will easily occur, therefore, it is not advisable to expand the air gap thickness when the torque constant is small. In addition, when the load torque required during the work of the driven disk is large, the air gap thickness should be reduced to ensure a larger output torque.



(b)

Fig. 3. The relation between output torque diagonal velocity and output power under different Angle difference

3.1 *Starting phase*

The angular velocities of the active and driven disks during the starting phase for different torque constants are listed in Table 3(where ω_M is the angular velocity of active disk and ω_S is the angular velocity of driven disk), the driven disk angular velocity fluctuates at the initial moment, and with the increase of time, the active and driven speeds gradually keep synchronized and the driven angular velocity stabilizes at about 1.6 s.

Table 3

Time dependence of active and driven speed during the start-up phase

Time (s)		0.4	0.8	1.2	1.6
ω_M (rad/s)		34.6	50.15	57.13	60.27
ω_s (rad/s)	K_t=0.0002	34.81	50.15	57.13	60.15
	K_t=0.0003	34.59	50.15	57.1	60.29
	K_t=0.0004	34.64	50.16	57.16	60.27

The angular velocity of the driven disk as shown in Fig.4(b) and Fig.4(c), when the active disk starts smoothly, the driven disk can keep synchronous rotation at the initial moment, but with the torque constant decreases, the angular velocity fluctuation of the driven disk becomes more sharp.

However, it is known from Eq.(8) that whether the driven disk can rotate synchronously is determined by damping coefficient and transient starting time together, and the angular velocity of the driven disk has a maximum value.

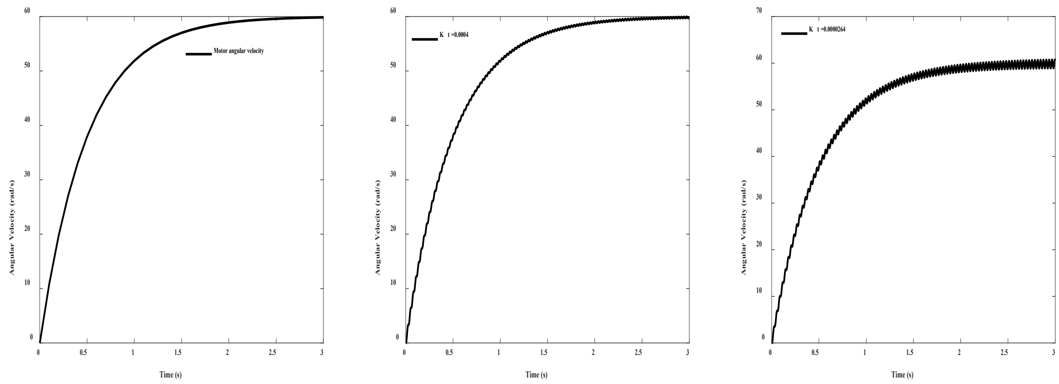


Fig. 4. Angular velocity dependence on time for different torque constants at a steady active disk speed of 60 rad/s. Kt is the torque constant.

Assume that the angular acceleration of the active disk is

$$a_M = \frac{d\omega_M}{dt} \tag{12}$$

ignore the effect of damping on the angular acceleration of the driven disk, and the maximum angular acceleration of the driven disk is

$$a_{S\,max} = \frac{T_{max} - Kt\omega_{S\,max}^2}{J} \tag{13}$$

where ω_{Smax} is the maximum angular velocity of the driven disk. when $a_M > a_{S\,max}$, the coupler is decoupled and the maximum angular velocity of the driven disk can be solved for as

$$\omega_{S\,max} = \sqrt{\frac{T_{max} - \frac{J\omega_0 e^{-t/\tau}}{\tau}}{K_t}} \tag{14}$$

The critical decoupling time and maximum angular velocity of driven disk under different torque constants are listed in Table 4, Where T_c is the critical decoupling time, $\omega_{S\,max}$ is the theoretical maximum angular velocity at critical decoupling using Eq.(14), ω_{emax} is the simulation value of maximum angular velocity at critical decoupling and σ is the error of both(where 2.64×10-5≤ K_t ≤4×10-4). The reason for the error is that the influence of damping is neglected in the theoretical analysis. The smaller the torque constant, the smaller the quadratic load driven by the driven disk will be, then the maximum angular speed of the driven disk will be larger. Therefore, with a known torque constant, the active disk starting and stabilizing speed should not be too large to ensure a smooth start of the magnetic coupler. When K_t<2.64×10^{-5}, the active and driven disks start to keep synchronous rotation.

Table 4

Critical decoupling time and maximum angular velocity at different torque constants

K_t	T_c (s)	ω_{smax} (rad/s)	ω_{emax}(rad/s)	σ(%)
0.0002	0.2923	232.0	214.8	7.41
0.0003	0.2326	178.4	178.4	5.41
0.0004	0.1987	162.9	156.2	4.11

3.2 *Acceleration phase*

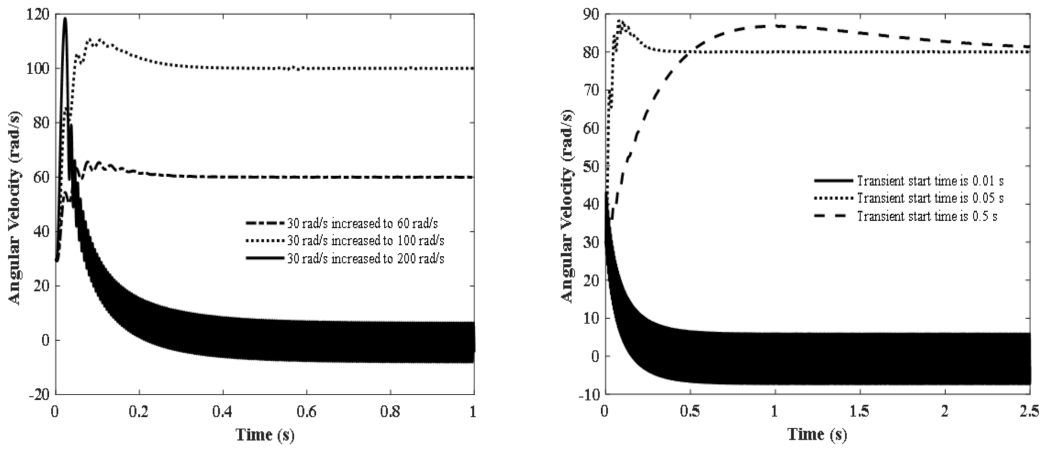
As is shown in Fig.5(a) that the relationship between driven disk angular velocity and time, when the active disk angular velocity of 30 rad/s is accelerated to different angular velocities during the stable operation phase at $K_t = 0.0003$. In the normal acceleration range, the driven disk vibrates greatly in the initial stage, and at about 0.3 s, the angular speed of the driven disk tends to stabilize and starts to keep synchronous motion with the active disk. However, when the active disk angular speed of 30 rad/s changes abruptly to 200 rad/s, the driven disk cannot keep synchronous motion with the active disk and the magnetic coupler system is unstable.

This is because the motor speed suddenly accelerates in a short period of time, the starting acceleration is very large, the active disk changes from a static state to a high-speed rotation state in a short time, at this time the magnetic lines of force generated by the active permanent magnet are also in a high-speed rotating state, which will cause the original active-driven air gap reluctance to increase, and the magnetic lines of force are only distributed along the path of minimum magnetic resistance. Most of the magnetic lines of force generated by the active permanent magnet finally act on the active disk itself, and the remaining small part of the magnetic lines of force continue to act on the stationary driven permanent magnet, resulting in vibration of the driven disk and thus decoupling occurs. Therefore, the conversion of the angular velocity of the driven disk must have a certain time margin.

To obtain this time margin, a critical transition time parameter is introduced. It is assumed that 99% of the time used in the process of the driven disk speed change is the critical transition time, the equation is satisfied as $e^{-t_m/\tau} = 0.01$, then the critical transition time is

$$t_m = 4.605\tau \tag{15}$$

To ensure that the active and driven disks can maintain synchronous rotation during the acceleration phase, then the active disk angular velocity change time must be greater than the critical transition time for the system to operate stably.



(b)

Fig.5. Effects of different accelerations and different transient start times on diagonal velocities

The change in angular velocity during the acceleration phase is related to the transient starting time in Eq.(15). From Fig.5(b), when the transient starting time is 0.5 s, the driven disk angular velocity reaches 80 rad/s at about 2.5 s, and the angular velocity tends to stabilize; when transient starting time is 0.05 s, the driven disk angular velocity reaches 80 rad/s at about 0.4 s. However, when the transient starting time is 0.01s, the driven disk cannot couple with the active disk causing decoupling, for reasons similar to those mentioned above for decoupling in the acceleration phase in Fig.5(a). Therefore, in order to ensure the stable operation of the system during the acceleration process, a relatively large transient starting time should be selected, or the air gap thickness should be reduced to lower the air gap reluctance.

3.3 *Deceleration phase*

The waveform of deceleration stage is shown in Fig. 6. when angular velocity of the active disk is reduced from 60rad/s to different target values, the vibration amplitude and the convergence time required for the stability of the driven disk are different. The reason for this result is that When the active disk suddenly decelerates, the driven disk still rotates at its original speed, resulting in the increase of reluctance between the two disks and the failure of smooth coupling of air gap flux density, leading to the vibration of the driven disk. From $n = \frac{60f}{p}$, the angular velocity of the two disks when rotating synchronously is $\omega_{s1} = \frac{4\pi f}{p}$ (where f is the disk rotation frequency, n is the speed of the active disk).

As the speed of the active disk decreases, the rotating magnetic field frequency decreases, and the damping and load effects of the driven disk start to decelerate and approach the target value, the larger the deceleration difference, the longer the time required. When the driven disk speed also approaches the target value, the air gap reluctance between the two disks gradually decreases, and most of the magnetic lines of force generated by the active and driven permanent magnets continue to couple and maintain synchronous rotation.

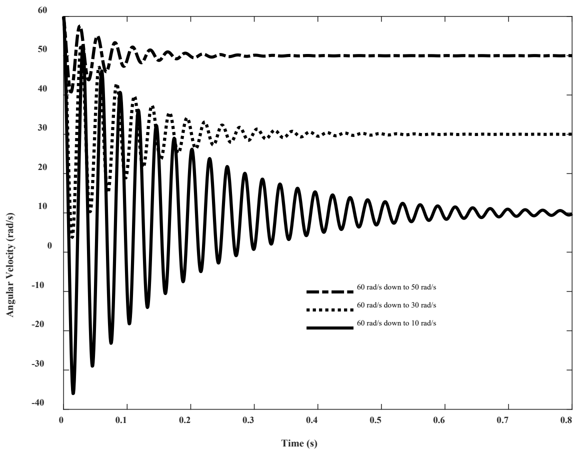


Fig. 6. The relationships between the angular velocity of the driven disk and time when the speed of the active disk is decelerated

4. Conclusions

1) The mechanical characteristic curves and power variation curves with angular velocity of disk synchronous magnetic coupler under different air gap thickness are obtained by simulation, and it is concluded that: the driven disk can start smoothly only when the load torque is less than the maximum torque; decreasing the air gap thickness will get more torque and more power; the smaller the air gap thickness, the larger the torque.

2) From the three different working phases of the driven disk, it is concluded that the speed of the active disk in the starting phase should not be too large. Smaller torque constants, the larger the maximum angular speed of the driven disk will be; in order to make the system run stably, a relatively large transient starting time should be selected during the acceleration phase to ensure that the active disk angular velocity change time is greater than the critical transition time. The speed of the driven disk can be decelerated to the target value in a short period of time with any deceleration difference when the parameters are kept constant in the deceleration process.

R E F E R E N C E S

[1]. *K Attallah, D* Howe, A novel high performance magnetic gear. IEEE Transactions. on Magnetics. 2001 Ju1; 37(4): 2844-2846.

[2]. *M Cong, T Li,* Design and application of magnetic coupling used for ultra-high vacuum robot. Proc. 15th Int. Conf. Mechatronics Mach. Vis. Pract. (M2VIP).2008 Dec; 346-351.

[3].*P O Rasmussen, T O Andersen, F T Joergensen, O Nielsen*. Development of a high performance magnetic gear. Industry Applications Conference 2003. 38th IAS Annual Meeting. 2003; 3 :1696-1702.

[4]. *M C Tsai, K Y Chiou, S H Wang , C K Lin,* Characteristics Measurement of Electric Motors by Contactless Eddy-Current Magnetic Coupler. IEEE Transactions on Magnetics.2014 Nov; 50(11): 1-4.

[5]. *Haixin Zhang, Dazhi Wang, Xingyu Wang, Xinghua Wang*, Equivalent Circuit Model of Eddy Current Device. IEEE Transactions on Magnetics, 2018 ;54(5): 1-9 .

[6]. *C H Chen, J Talnagi, J Liu, P Vora, A Higgins, S. Liu*, The effect of neutron irradiation on Nd-Fe-B and Sm/sub 2/Co/sub 17/-based high-temperature magnets. IEEE Transactions on Magnetics. 2005 Oct; 41(10): 3832-3834 .

[7]. *Zheng B, Zheng J, Si S, Ren Y, Xu X, Deng Z.,* Magnetic Characteristics of Single-Block and Multi-Block Nd-Fe-B Permanent Magnets at Low Temperature. IEEE Magnetics Letters. 2016; 7: 1-5.

[8]. *K C Min, J Y Choi, J M Kim, H W Cho, S M Jang*, Eddy-Current Loss Analysis of Noncontact Magnetic Device With Permanent Magnets Based on Analytical Field Calculations. IEEE Transactions on Magnetics. 2015 Nov; 51(11): 1-4.

[9] .*P Elies, G Lemarquand*., Analytical optimization of the torque of a permanent-magnet coaxial synchronous coupling. IEEE Transactions on Magnetics, 1998; 34(4): 2267-2273 .

[10]. *Furlani E P, Wang R, Kusnadi H.*, A three-dimensional model for computing the torque of radial couplings. IEEE Transactions on Magnetics. 1995; 31(5): 2522-2526.
[11]. *Zhao K Z.,* [Theoretical design and application of magnetically coupled drive technology and devices]. Beijing(China): Hua xue gong yie chu ban she; 2018. Chinese.
[12]. *Zhiyi Yang, Han Zhao,* Calculation and characteristic analysis of axial force and transmission torque of axial magnetic coupling. J Magn Devices. 2001; 32(6):1001-3830