ARTICLE IN PRESS

ISA Transactions xxx (2018) 1–11

Contents lists available at ScienceDirect

ISA Transactions

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

Research article

Linear magnetic clutch to automatically control torque output

Nan-Chyuan Tsai*, Chi-Ting Yeh, Hsin-Lin Chiu

Department of Mechanical Engineering, National Cheng Kung University, 70101, Tainan City, Taiwan

ARTICLE INFO

Article history:
Received 17 October 2017
Received in revised form
6 March 2018
Accepted 26 March 2018
Available online xxx

Keywords:
Torque tracking control
Magnetic clutch
Relative angular velocity
System stability

ABSTRACT

A novel eddy-current Magnetic Clutch (MC) unit with its torque-adjustable mechanism is proposed by this research. As to mechanical structure, the MC unit is mainly constituted by a squirrel-cage inner rotor and a magnet-embedded outer rotor. The transmitted output torque can be adjusted by either the Overlapped Length (OL) or the relative angular velocity between outer rotor and inner rotor. Firstly, the mathematical model of the MC system is developed. Secondly, the features and characterization of the MC unit are explored by intensive experiments under various overlapped length and relative rotational speed between inner rotor and outer rotor. The major novelties of the MC system unit include: (i). being very handy to operate even for non-professional users, (ii). the output torque of the proposed MC can be adjusted automatically, and (iii). the proposed MC can be easily incorporated to any torque control system. To examine the validity of the MC unit, two control strategies, i.e., PID action and pole-placement method are presented and compared for the performance of the closed-loop feedback systems. In addition, the locations of system roots are found to ensure the stability of the torque control loops. At last, several experiments are undertaken, including constant torque control and variable torque control. Particularly, an experiment of screw-driven into a wooden board is conducted to illustrate the drilling quality much upgraded by the proposed torque control device. Besides, a couple of torque-tracking experiments realistically manifest the quick response and high precision of the MC unit. In summary, either for stability or performance, the proposed MC feedback system is eligible to execute superior torque tracking or torque regulation.

1. Introduction

Magnetic Clutches (MCs) have many advantages such as being contactless, reduction of vibrations, no need to align precisely between shaft and clutch, and a certain degree of protection against light overload [1]. Hence MCs are gradually employed in a few industries to realize torque transmission [2,3], reaction to variable loading [4] or torque measurement [5]. MCs can be mainly categorized into three types: permanent-type [1–3,6–9], eddy-current-type [5,10–17] and magnetorheological-fluid-type [4,17–24]. Among these types, the permanent-type MCs possess the merits such as simpler structure, higher torque density, and less heat generation. The magnetorheological-fluid-type MCs have the merits such as high torque density, and handy to alter the extent of transmission torque by controlling the external magnetic field. The eddy-current-type MCs possess the merits such as soft start-up, no need to align rotor with respect to clutch precisely, easier to adjust the torque, and a certain degree of shock attenuation.

In recent years, numerous researchers conducted investigations on MCs and derived the corresponding analytical/numerical models [1,5,6,10,11,15,16,18]. The most common issue is to discuss the relation between the air gap and transmission torque [12,13]. The effects on the transmission torque by eddy-current MC under different materials of conductive disks were discussed by Canova and Vusini [14]. Moreover, Canova and Vusini also studied the transmission torque under two different designs of MC [11]. The torque transmission and heat distribution under various numbers of slots on the slotted conductor disc were addressed by Gao et al. [13]. Tian et al. explored the influences on the disk deformation of the disk-shape magnetic clutch with respect to transmission torque [20]. Ose et al. presented the influence by width and number of permanent magnets on the transmission torque [7]. However, the research regarding the torque control by the adjustable eddy-current MCs has hardly been reported. Hence a novel eddy-current magnetic clutch with its torque-adjustable mechanism is proposed by this paper.

The magnetic clutch is mainly constituted by a squirrel-cage inner rotor and a magnet-embedded outer rotor. The mechanical

* Corresponding author.
E-mail addresses: nortren@mail.ncku.edu.tw, z9208014@email.ncku.edu.tw (N.-C. Tsai).

https://doi.org/10.1016/j.isatra.2018.03.020
0019-0578/

structure of inner rotor of MC is equal to that of the squirrel cage popularly adopted by induction machines [25–28]. To establish a relatively more intensive magnetic field to enclose the squirrel cage, i.e., inner rotor, twelve permanent magnets are embedded in the outer rotor. The magnetized direction of these permanent magnets at the outer rotor is in ***Halbach*** array [29–32] to construct a relatively stronger uniform magnetic field. Therefore, the relation between the output torque and the Overlapped Length, abbreviated as OL which will be defined in details in Section 2.1, between inner rotor and outer rotor, becomes more intuitive, simpler and relatively linear. The schematic diagram of torque control by proposed magnetic clutch is shown in Fig. 1. By portraits, OL and the relative angular velocity between the outer rotor and the inner rotor, denoted by ℓ and $\Delta\varpi$ respectively, are shown in Fig. 1 as well. How much the torque is transmitted by the proposed MC can be adjusted by the OL *via* a linear motor.

In this paper, the analytical model of transmission torque is derived at first. Secondly, the analytical model is verified by intensive experiments under various OL and relative rotational speeds between outer rotor and inner rotor. Subsequently, a few experiments are undertaken to explore the characteristics of the proposed closed-loop control system including the innovative magnetic clutch. In addition, the effect of magnetic hysteresis, due to the displacement loop of the OL, between outer rotor and inner rotor, which undergoes extension (half cycle) and contraction (the other half cycle), is assessed. At last, the efficacy of the magnetic clutch is verified and examined by intensive experiments to undertake constant-torque and continuously-variable-torque applications for industries.

The proposed MC has few advantages such as (i) the mechanical structure is very simple, light in weight and small-sized in space, (ii) the torque transmitted can be controlled either by the relative angular speed between outer rotor and inner rotor, or the Overlapped Length (OL) *via* a linear motor, (iii) it is very handy to operate as long as the OL can be adjusted to slide axially by any means, (iv) it is advantageous to mount it upon a rotary shaft or load since the frame structure of MC is of bi-cylinders and co-axial, (v) no need of an inverter to be additionally equipped, and (vi) the power source to the MC is not merely limited to an induction motor. Instead, it can be any rotary power source, e.g., DC motor, wind turbine, flywheel.

2. Design and mathematical model of torque-adjustable magnetic clutch

2.1. Design of torque-adjustable magnetic clutch

The schematic diagram of the proposed torque-adjustable Magnetic Clutch (MC) is shown in Fig. 2. Its specification and major characteristics are listed in Table 1. The magnetic clutch is mainly constituted by a squirrel-cage inner rotor and a magnet-embedded outer rotor. The outer rotor is supported by a stand and the stand is connected to a linear motor. It is noted that the "***axial***" position of the inner rotor is fixed while the "***axial***" position of the outer rotor can be adjusted by the linear motor. In order to establish a relatively stronger uniform magnetic field, there are twelve grooves designed to house permanent magnets along the inner wall of the outer rotor. The magnetized directions of the flux lines of these twelve permanent magnets are orderly varied and shown in Fig. 3 to construct a typical ***Halbach*** cylinder. Hereby, the Overlapped Length (OL), shown in Fig. 2, in fact represents the overlapped length between the permanent magnets embedded in the outer rotor and the squirrel-cage rotor, i.e., the inner rotor, along the axial direction. As the OL is increased, shown in Fig. 2(a), the output torque by the MC is accordingly enhanced. On the contrary, as the OL is decreased, shown in Fig. 2(b), the output torque is decreased instead. The OL is tuned according to (i): the output torque actually required by the user, (ii): the axial position of the outer rotor and (iii): the relative angular speed between outer rotor and inner rotor. The axial position of the outer rotor can always play the role of the feedback and can be precisely controlled by the linear motor. Besides, a rotary torque sensor is employed to measure the output torque of the MC and the angular speed of inner rotor while an optical tachometer is employed to acquire the angular speed of the outer rotor. By the feedback of these real-time measurements above, the output torque of the MC can be exactly and precisely controlled to the desired level in real-time sense. Actually, the aforesaid torque sensor can be replaced by a state observer [33–35] if the cost of the MC system has to be reduced while the precision can be scarified to some extent.

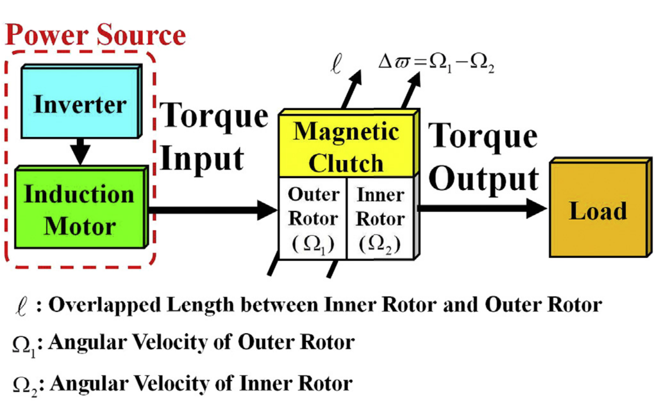

Fig. 1. Schematic diagram of torque control by proposed magnetic clutch.

2.2. Mathematical model of torque-adjustable magnetic clutch

The magnetic flux lines by the rotary outer rotor intersect the conductive bars of the squirrel cage. According to Faraday's law for electromagnetic induction, electric currents are hence induced to flow into the conductive bars. As long as the electric currents perform, another magnetic field is therefore generated at the squirrel cage. At the same time, the inner rotor is driven to rotate in the direction of magnetic flux by this induced magnetic torque. The schematic diagram of a squirrel cage, corresponding to a certain magnetic field at certain time epoch, is shown in Fig. 4.

where

$\vec{B}_f$: Magnetic field by outer rotor
$\Delta\varpi$: Relative angular velocity between outer rotor and inner rotor
r: Radius of the squirrel cage
L: Length of conductive bars
ψ: Skew angle of the conductive bars

In Fig. 5, the squirrel cage, with "***n***" conductive bars, rotates along the z-axis at the speed, $\Delta\varpi$, within a magnetic field, $\vec{B}_f$. At time instant t, the angular position of the k^{th} conductive bar on the $(\vec{u}_x,\ \vec{u}_y)$-plane is:

$$\theta_k = \Delta\varpi t + \frac{2\pi k}{n}\ , k = 1, 2, 3, \ldots, n. \tag{1}$$

where n is the number of conductive bars. By Lorentz force law, the induced electromagnetic force upon the k^{th} conductive bar within uniform magnetic field is: