EVALUATION OF DC MOTORS FOR CLAMPING FORCE MECHANISM IN AN ELECTRO-MECHANICAL CONTINUOUSLY VARIABLE TRANSMISSION

Article history
Received
24 November 2019
Received in revised form
26 December 2019
Accepted
29 November 2019
Published Online
29 November 2019

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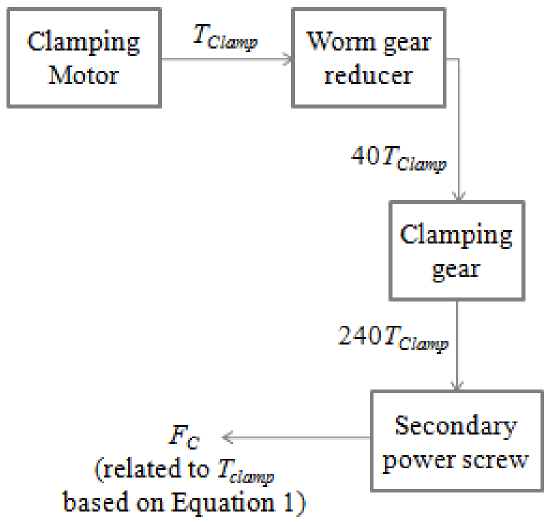
Graphical Abstract



Abstract

Continuously variable transmission (CVT) uses a metal pushing V-belt and pulley system to vary its ratio between the transmission's input and output. Conventionally, the ratio and the belt's clamping force are adjusted using a hydraulic system. However, during operation, continuous hydraulic pressure is required to ensure that the belt's clamping force is always sufficient, resulting in a rather significant losses in the CVT. Thus, an electro-mechanical CVT (EM CVT) is proposed, where the hydraulic system is replaced with a power screw system actuated by a DC motor. As a result, the aforementioned losses can be eliminated since the clamping force can be maintained using the self-lock capability of the power screw system. In this paper, the performance of various DC motors are evaluated, in terms of rated torque, size and weight, so that the most suitable one can be determined for application in the EM CVT. Based on the evaluation process, DC motor type D5BLD450-24A-30S from DMKE Motor Co. is selected since it has a rated torque of 1.4Nm (ranked 2nd highest, the highest at 1.8Nm), relatively small size with a length of 107mm (ranked the smallest) and a weight of 3.2kg (ranked 2nd lowest, the lowest at 3.0kg).

KEYWORDS

Electro-mechanical, continuous variable transmission, DC motor, clamping force, automotive applications

INTRODUCTION

Fuel economy of a car is one of the most important criteria which is greatly influenced by the efficiency of the transmission used. In general, there are many types of transmission currently used for automotive applications and continuously variable transmission (CVT) is one of the most popular types due to its capability to vary the ratio continuously between its maximum underdrive and overdrive. Such capability allows the engine to be operated in its most efficient range, hence making the car's fuel consumption low. However, CVT requires continuously high hydraulic pressure to clamp the metal pushing V-belt sufficiently. The hydraulic pressure is conventionally generated by an oil pump which is powered by the car's engine. As a result, a significant amount of the engine power is diverted to clamp the belt, thus the gain in terms of efficiency due to the CVT's continuous ratio range is cancelled out.

To address the issue, researchers from Universiti Teknologi Malaysia (UTM) propose the idea of electro-mechanical CVT (EM CVT). Beside UTM's researchers, there are also other researchers that have developed their own designs of EM CVT (Rahman *et al*., 2018 and Liu *et al*., 2018). In the UTM's EM CVT, specifically, the ratio is varied using a DC motor (ratio motor) and its power screw system, while the clamping force applied on the metal pushing V-belt is adjustable through another DC motor (clamping motor) with its power screw system (Tawi *et al*., 2015 and Mazali *et al*., 2017). The adjustment is carried out on the CVT's secondary pulley and the clamping force is defined based on the deflection of two disc springs assembled inside the secondary pulley assembly (Figure 1). Once the desired ratio and clamping force are achieved, the thread of the power screw is used to maintain them. Thus, in contrast to the conventional CVT, no diversion of engine power occurs in the EM CVT. The required clamping force for the EM CVT is around 20kN, thus the clamping motor must be able to produce sufficient torque so that the force requirement can be achieved (Mazali *et al*., 2015).

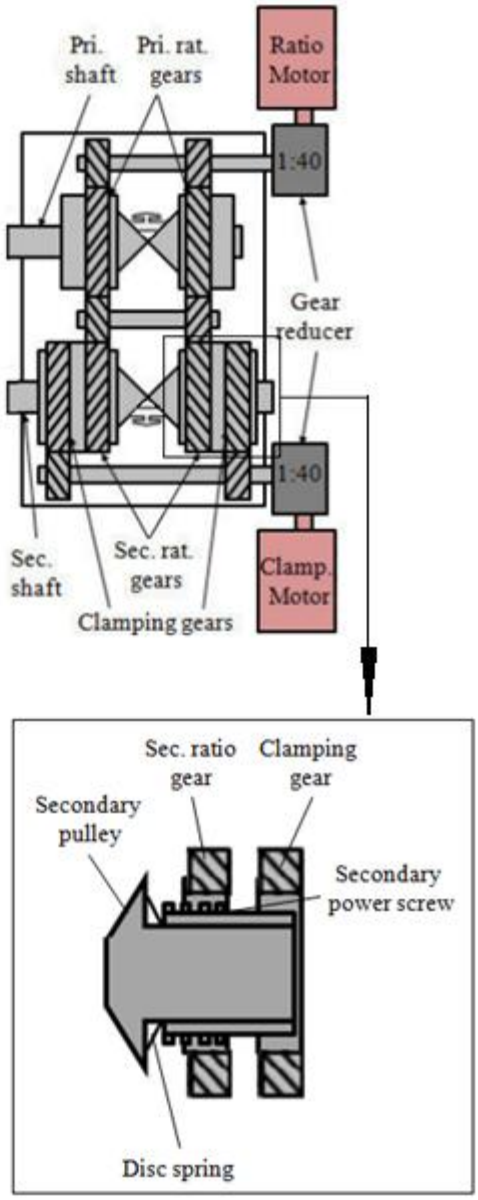


Figure 1: Clamping force mechanism in the EM CVT's secondary pulley assembly [4]

CLAMPING FORCE MECHANISM

In the clamping force mechanism of UTM's EM CVT, the clamping motor provides input torque to a worm gear reducer with a ratio of about 40.00. Next, the torque from the worm gear reducer is transferred to the clamping gears with a ratio of 6.00. The clamping gears are connected to the secondary power screws through pins, thus the rotation of the clamping gears will cause the secondary power screws to be rotated together. The secondary power screws, on the other hand, are also meshed with the secondary ratio gears through threads and the secondary ratio gears' rotation is determined by the torque of the ratio motor. Therefore, because of the rotation of the clamping gears, the secondary power screws will be moved axially, resulting in the change of the belt's clamping force through the deflection of the disc springs. Figure 2 illustrates the process of adjusting the belt's clamping force in the clamping force mechanism.

Based on the process shown in Figure 2, relationship between the torque of the clamping motor and the belt's clamping force can be defined as Equation 1. The equation is derived based on a basic equation to calculate the required torque to lift a screw against a load, where the load in this case represents the belt's clamping force. In Equation 1, T_{clamp} represents the required clamping motor's torque to achieve the desired clamping force (F_c). Other parameters in the equation are described in Table 1. Hence, the torque required from the clamping motor to achieve the range of F_c from around 2kN to 20kN can be calculated as shown in Table 2. Based on the calculation, the clamping motor must be able to produce about 1.13Nm of torque so that the clamping force of 24.4kN can be reached.

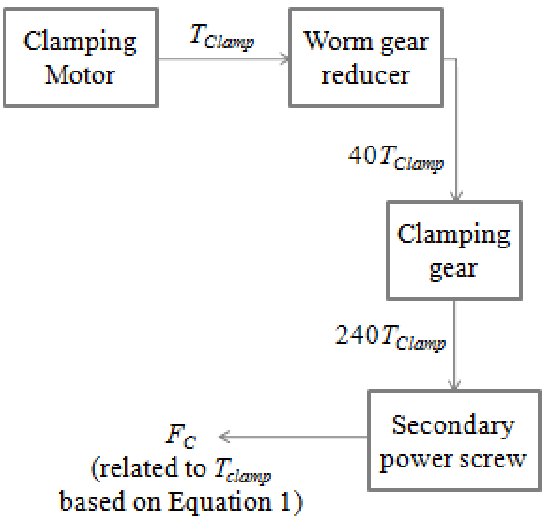


Figure 2: Process of adjusting the clamping force using clamping motor's torque

Table 1: Parameters for Equation 1

Descriptions	Unit	Value
mean diameter of power screw, d_{ps}	m	0.08551
Friction coefficient of power screw surface contact, f	-	0.16
Pitch of power screw, l	m	0.002
Overall ratio (ratio of the worm gear times ratio of the clamping gear), G	-	240

Table 2: Experimental results

Clamping Force, F_c (kN)	Motor torque, T_{clamp} (Nm)
1.6	0.07
8.0	0.37
11.2	0.52
16.0	0.74
24.4	1.13

$$T_{clamp} = \frac{F_c}{G}\left[\frac{(\pi f d_{ps} - l)}{(\pi d_{ps} + f l)}\right] d_{ps} \qquad (1)$$

Evaluation of Motors

Currently, the prototype of EM CVT described in this paper uses a brushless DC motor BM-370 as the clamping motor. The motor is provided by Adlee Powertronic Co. and it has a capability to give a rated torque of 1.18Nm at 3000RPM. Further specifications of the motor are depicted in Table 3. While the motor generally meets the requirements for the clamping force mechanism, its size is rather big. Thus, it is desirable to re-evaluate other motors as a possible option for the belt's clamping application.

Table 3: Specifications of BM-370 DC motor (the original clamping motor) [6]

Motor Type	BM-370
Rated voltage (Volt)	24
Rated speed (RPM)	3000
Rated torque (Nm)	1.18
Peak torque (Nm)	3.92
Length (mm)	169.5
Weight (kg)	5.0

The selected motors for evaluation are BLDC 1.25-100, 86BLS98 and D5BLD450-24A-30S (Table 4) [7, 8, 9]. All of these motors are brushless DC motors which means they are of the same type as the one currently used in the EM CVT. In terms of torque capability, all of them are capable of producing a rated torque of 1.8Nm, 1.4Nm and 1.4Nm, respectively. Thus, the three motors are capable of producing about 19% to 53% higher rated torque as compared to the original clamping motor. High torque capability means the time taken to adjust the desired clamping force can be shorten. However, for BLDC 1.25-100, although its rated torque is the highest, its rated speed is significantly lower (2500RPM) as opposed to the original clamping motor (3000 RPM). Therefore, the gain in terms of its high rated torque is compromised. For 86BLS98 and D5BLD450-24A-30S, their rated speed is the same as the original clamping motor.

Table 3: Specification of three brushless DC Motors in the Market [7, 8, 9]

Motor Type	BLDC1.25-100	86BLS98	D5BLD450-24A-30S
Rated voltage (Volt)	24	48	24
Rated speed (RPM)	2500	3000	3000
Rated torque (Nm)	1.8	1.4	1.4
Peak torque (Nm)	6.4	4.2	4.3
Length (mm)	172	112	107
Weight (kg)	6.0	3.0	3.2

For size comparison, D5BLD450-24A-30S is the most compact with the length of 107mm, followed by 86BLS98's 111.5mm. Both of these motors are significantly smaller as compared to the original clamping motor (169.5mm). BLDC 1.25-100, on the contrary, is slightly bigger than the original one, with its length at 172mm. Finally, in terms of weight, 86BLS98 is the lightest at 3.0kg, followed by D5BLD450-24A-30S (3.2kg), the original motor (5.0kg) and finally BLDC 1.25-100 (6.0kg). Nevertheless, 86BLS98 requires higher voltage for operation (48V) while the other evaluated motors need a rated voltage of 24V. This means that the motor needs bigger battery for its operation. As such, among the four evaluated motors (including the original clamping motor), D5BLD450-24A-30S is chosen as the most suitable selection for the clamping force mechanism.

Conclusions

As a conclusion, the torque requirement for the clamping force mechanism of the EM CVT has been successfully analyzed. From the analysis, the amount of torque required to reach the belt's clamping force of 24.4kN is around 1.13Nm. Next, the original clamping motor used in the clamping force mechanism has been compared with three other brushless DC motors. Based on the comparison, D5BLD450-24A-30S is decided as the best option to replace the original one (BM-370) since it offers higher rated torque (1.4Nm as opposed to 1.18Nm), smaller size (length of 107mm as opposed to 169.5mm) and lightweight (3.2kg as opposed to 5kg). For future works, further analyses, particularly on the efficiency and durability of these motors, are still required to ensure that the most suitable motor can be selected for application in the clamping force mechanism of the EM CVT.

Acknowledgement

Authors would like to thank Universiti Teknologi Malaysia (UTM) for providing funding to this project through GUP Tier 2 Grant (Q.J130000.2651.16J75).

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