

Design of an Eddy Current Torque Bypass Clutch for Seamless Automated Manual Transmissions of Electric and Hybrid Vehicles

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ABSTRACT

This paper presents the design and experimental validation of an eddy current torque transfer clutch for use inside Automated Manual Transmissions (AMTs) to perform seamless gear upshifts. Electric vehicles (EVs) with a single-ratio gearbox may provide high levels of smoothness, but using a multi-speed gearbox provides significant benefits in terms of vehicle acceleration, top speed, powertrain cost, mass, and energy consumption. AMTs can provide smooth shifts without torque interruption when coupled to a normally-open torque bypass clutch. However, conventional dry friction clutches are not best suited for such torque bypass due to wear and controllability concerns, while wet clutches would decrease powertrain efficiency due to viscous losses. An eddy current clutch would be highly controllable, simple to manufacture, low-cost, robust, and do not wear compared to friction clutches. The potential of eddy current clutches is assessed from a representative case study consisting of a ~ 190 Nm clutch for a seamless two-speed AMT. The clutch design is based upon Wouterse's model, which is further refined using a Finite Element Analysis (FEA) on the clutch magnetic circuit. A prototype clutch is built and installed inside an existing AMT. The measured clutch coupling torque agrees well with Wouterse's model results, with a maximum error of 6%. The AMT performed seamless gear upshifts on a test bench thanks to the eddy current clutch, which confirms their viability for torque bypass.

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INTRODUCTION

Motivation

A general trend is observed in the automotive industry toward driving comfort and shift quality improvement, which prompts car makers to shift from interrupted traction force transmissions to seamless transmissions [1, 2]. Automatic Transmissions (ATs) and Continuously Variable Transmissions (CVTs) can shift smoothly but they are not the best candidates for multi-speed transmissions in EVs because they have reduced efficiency compared to Manual Transmissions (MTs) and they are more expensive to manufacture due to their high complexity [1, 3]. An AMT coupled with a torque bypass clutch, which is also known as a Parallel Gearshift Transmission (PGT) [4], could overcome ATs and CVTs efficiency limitations while offering identical driving comfort levels and being low-cost.

Similarly to internal combustion engine vehicles, electric traction motors in EVs can advantageously be coupled with a multi-speed transmission to provide significant benefits in terms of vehicle acceleration, top speed, powertrain cost, mass, and energy consumption (from 4% to 15% [5, 6, 7, 8]). The latter is critical to maximise EVs range considering the scarcity of on-board energy for traction.

A dry friction clutch is not the best device for intermittent torque bypass inside PGTs during a gear upshift because it has to dissipate a large amount of kinetic energy to slow down the traction motor. The problem worsens for EVs when the electric motor runs at $>10,000$ Revolutions Per Minute (RPM). The dry clutch friction liner pad has to absorb much energy, raising wear concerns. High power dissipation in the liner would also affect transmitted torque (heat fading) and controllability [9]. A wet clutch can absorb higher energy levels than a dry clutch, but it has residual drag torque when not in use, which is undesirable from an energy efficiency point-of-view since the torque bypass clutch inside the PGT is normally open. Wet clutches also need a hydraulic control unit, adding to the total cost and complexity of the system.

An eddy current clutch relies on electromagnetic forces to create a coupling torque. These clutches could address the problems affecting friction clutches (wear and control) as well as being highly controllable, simple to manufacture, low-cost, robust, and having no off-state torque. This paper discusses the design and experimental validation of an eddy current clutch for torque bypass in seamless AMTs.

Background and Literature

The proposed eddy current clutch works as follows. A MagnetoMotive Force (MMF) source (either an electromagnet or a permanent magnet) produces a magnetic flux. This flux induces an eddy current in the clutch disc, which in turn produces a magnetic field that opposes the original flux, creating a repulsive force between the disc and the magnet. This force is used to create a coupling torque.

magnetic circuit (Figure 1). A stator carries the magnetic flux to a toothed rotor. The teeth of the toothed rotor channel the magnetic flux across the drum rotor such that the magnetic flux has maximum density (B_{max}) under the teeth and minimum density (B_{min}) in-between. When the drum rotor revolves at a different speed than the toothed rotor, the magnetic flux density across the drum rotor starts varying with position, which induces eddy currents inside the drum (Faraday's law of induction). The eddy currents interact with the magnetic flux of the toothed rotor to create an electromagnetic coupling force between the two rotors (Lorentz force principle). The magnitude of these forces is controlled by varying the magnetic flux density (with the variable MMF source) and they can be computed indirectly with the eddy currents resistive losses (RI^2) [10] or with Maxwell stress tensor [11, 12].

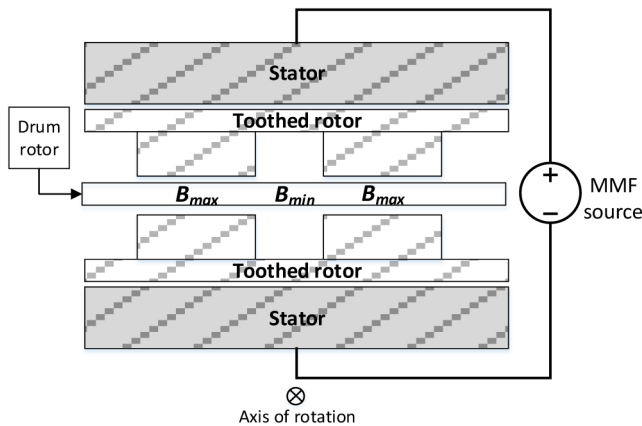


Figure 1. (Unrolled) Schematic view of the clutch

While Maxwell stress tensor can determine the magnitude of electromagnetic forces for various electromechanical devices, it does not directly give relations between the eddy current clutch geometrical dimensions and the torque versus slip speed profile. Wouterse proposed a 1-dimensional (1D) model that relates the clutch geometrical dimensions to the clutch torque versus slip speed profile [10], which is helpful for performing parametric studies for designing the clutch.

Wouterse's model requires knowing B_0 (the difference between the minimum (B_{min}) and the maximum (B_{max}) magnetic flux density across the rotor). Computing the magnitude of B_0 is nontrivial because the magnetic flux fringes in-between the toothed rotor teeth and causes B_{min} to be small but non-zero. Electrical machine design uses Carter's factor [13] to compute an equivalent magnetic flux density B_0 given the teeth geometrical parameters. Carter's factor has been derived for various teeth shapes [14] as well as for doubly toothed structures [15] (similar to Figure 1).

The toothed rotor teeth could be replaced by permanent magnets to produce the required magnetic flux (such as in axial [16] or radial [17] magnetic couplings). Permanent magnets require an external actuation mechanism to insert or retract them from the clutch magnetic circuit in order to vary the magnetic flux and coupling

force, which adds to the clutch complexity. Therefore, only electromagnets will be considered in this paper because they do not require such mechanisms.

Recent modeling work on eddy current devices attempts to achieve higher accuracy in magnetic field calculation by taking into account the effects of iron saturation and of the rotor reaction field (due to eddy currents) in torque versus slip speed calculations [18]. An exact analytical computation of magnetic flux density and eddy currents inside the conductive rotor remains complex because of the system 3-dimensions (3D) geometry. A transient magnetic FEA is required to precisely estimate both the actual magnetic flux densities and eddy currents paths in order to compute the torque versus slip speed profile. A transient FEA model involves solving complex equations on each node including non-linearity (such as magnetic saturation in the iron), movement, and skin effect [19]. Their usefulness as a design tool is limited due to the large computational times they required for solving. Analytical models therefore remain handy tools to quickly study various eddy current devices configurations, a motivation in this paper for using Wouterse's analytical model for the clutch design.

Methodology

The powertrain characteristics of an EV test platform, the seamless gearbox architecture and the eddy current torque bypass clutch structures are presented. The EV test platform and its AMT provide realistic design requirements for the eddy current clutch. These specifications allow computing the eddy current clutch critical torque (maximum coupling torque) and critical slip speed (slip speed producing maximum coupling torque) that are required to proceed with design.

The clutch is sized using Wouterse's model from the previously computed critical torque and slip speed. Values are gradually assigned to Wouterse's model while ensuring that the resulting design complies with physical and magnetic constraints. A magnetostatic FEA on the clutch magnetic circuit verifies if magnetic saturation occurs and helps choosing the number of turns for the electromagnet.

An eddy current clutch prototype is built and retrofitted into an EV test platform two-speed custom AMT. The clutch torque versus slip speed profile is measured and compared to Wouterse's model predictions. Gear upshifts are performed using the modified AMT to validate that eddy current clutch can indeed be used for torque bypass during a gearshift.

Results and Conclusion

The largest error between the measured and computed critical torque value is smaller than 6%, which validates the use of Wouterse's model for designing an eddy current clutch. The eddy current clutch provides torque fill-in during a gear upshift, confirming their viability as torque transfer clutch for seamless AMTs.

VEHICULAR ENVIRONMENT, SEAMLESS GEARBOX AND EDDY CURRENT TORQUE BYPASS CLUTCH

Vehicular Environment

The clutch is designed to be retrofitted into an existing AMT of a full-electric modified Volkswagen Golf GTI for a proof-of-concept (Figure 2). Table 1 contains the vehicle specifications, the powertrain characteristics and the clutch requirements for seamless AMT operation. The clutch diameter and axial length are constrained by the existing AMT size and by the engine bay free space. The required coupling torque and operating slip speed are determined by the AMT ratios and by the electric traction motor power.



Figure 2. Electric Volkswagen Golf GTI from Projet Phoebus - Université de Sherbrooke

Seamless Gearbox Architecture

Figure 3-a shows the basic two-speed seamless AMT with the eddy current torque bypass clutch, with no gear engaged (neutral position). In this design example, all three gear ratios are constrained by the use of the existing AMT. For a new gearbox design from scratch, the first and second gears would be selected to maximize powertrain efficiency as well as vehicular acceleration and top speed [8]. The third gear would be chosen to minimize the critical torque of the eddy current clutch.

Figure 3-b, -c and -d show a gear upshift sequence. The power transfer from the electric traction motor to the vehicle wheels follows the blue line. The motor is engaged in first gear at the beginning (Figure 3-b). When the electric motor reaches its maximum rotational speed (motor is then in constant power mode), a gearshift begins by setting the motor commanded torque to 0 Nm (the driver's accelerator pedal is bypassed). The gear selector (red component) moves into neutral position. The Transmission Control Unit (TCU) activates the eddy current torque bypass clutch at the same moment the gear selector is disengaged to minimize the torque interruption to the output shaft (Figure 3-c). The eddy current clutch then develops a coupling torque such that the same torque magnitude is applied on the AMT output shaft compared to when the traction motor was engaged. The traction motor loses rotational kinetic energy to the wheels through the eddy current clutch and it slows down until the second gear on the input shaft revolves at the right speed for its

engagement by the lay shaft via the gear selector. The TCU disables the eddy current clutch (Figure 3-d) at the same moment the gear selector engages the second gear. The gear upshift sequence ends by giving the motor control back to the driver's accelerator.

Table 1. Applications requirements for clutch design

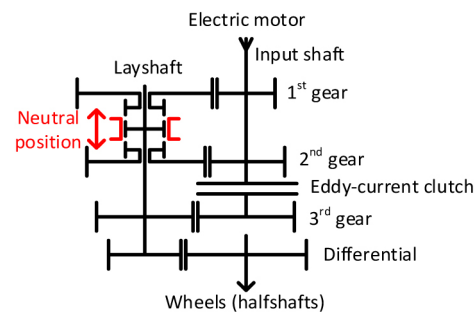
Characteristics	Values	Units
Maximum external diameter	264	mm
Maximum axial length available to retrofit clutch in existing AMT	90	mm
Required clutch coupling torque	193	Nm
Maximum motor power	80	kW
Maximum motor torque	170	Nm
Motor shaft maximum rotational speed	10 000	rpm
Input shaft equivalent inertia (with electric motor)	0.15	kg•m ²
Heat released at each usage (motor at maximum power and speed, no regenerative braking)	27	kJ
Nominal traction battery voltage	350	Vdc
AMT first gear ratio	33:10	---
AMT second gear ratio	35:18	---
AMT third gear ratio	34:26	---
Operating slip speed range (v_{max} to v_{min})	6037 to 1929	rpm

Eddy Current Torque Bypass Clutch

Figure 4 is a 3D view of the clutch. Figure 5-a shows a cross-sectional axial view and Figure 5-b is an unrolled frontal view. Figure 5 also presents the clutch design parameters (described in Table 2). Table 2 contains the prototype clutch dimensions (discussed in section Clutch design using Wouterse's model).

The electromagnet does not revolve and it is fixed to the stator. No brushes or slip rings are required to power it, which enhances the system reliability and robustness.

This clutch aims to be low-cost. Therefore, the stator and toothed rotors are made of cheap AISI 1018 steel and the drum rotor is made of aluminum.



a. Two gears AMT with torque bypass clutch

Figure 3. AMT with eddy current torque bypass clutch