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# Modeling, analysis and constrained control of wet cone clutch systems: A synchromesh case study☆

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A B S T R A C T

This paper addresses the problem of controlling the regime of lubrication in sliding lubricated surfaces with the purpose of wear reduction and the lifetime increase of the friction lining material. To this end, the hydrodynamic, mixed, and boundary lubrication regimes in a cone clutch system are experimentally investigated and a piecewise linear approximation of the Stribeck curve is presented. The friction-induced temperature rise and its effect on viscosity reduction, wear, and dynamic uncertainty are discussed. A modified wear model of the cone clutch is proposed by taking into account the contributions of both the mixed and boundary lubrication regimes. Using the obtained wear model, the necessity of the operation in the mixed lubrication regime is shown, and the duration of the operation is determined. The dynamical model of the system is constructed and the friction-induced instability of the system in the mixed lubrication regime is investigated and discussed. The operation in the mixed lubrication regime together with the friction-induced instability reveals the need for a closed-loop control system. Employing the obtained dynamical, frictional, and wear models, a controller design method is developed to meet the objectives and satisfy the constraints. The proposed controller design method results in a piecewise affine (PWA) feedback law obtained by solving a set of linear programming (LP) problems offline. The resulting controller is easily implementable in real time. The robust stability of the proposed closed-loop control system is proved considering the uncertainties of the dynamical system. The robust performance of the PWA closed-loop control system in the presence of various disturbances is assessed through simulation and confirmed by experiments conducted on a test rig. The case study here is the engagement process of a synchromesh system in a clutchless automated manual transmission of an electric vehicle.

## 1. Introduction

Modeling the frictional dynamics, wear and failure of mechanical systems for control, friction compensation and lifetime estimation requires comprehensive knowledge of friction phenomena [1,2]. Friction clutches are mechanical devices that are extensively used in mechanical systems in order to transfer the power from one rotating element to another through the friction between two or more rotating parts. Cone clutches are a special type of friction clutches whose mating surfaces are conical. Such clutches are comprised of female and male conical parts. For consistency with previous literature on cone clutch systems, hereafter the female and male conical parts are referred to as ring and cone, respectively [3,4]. In comparison with the disc clutches, the conical configuration of a cone clutch causes the wedging action which results in higher pressure between the contact surfaces and consequently higher frictional torque. The wear and temperature of cone clutches are often managed by the use of an oil lubricant which leads to a wet cone clutch system [5,6]. The frictional behaviour of the wet cone clutch systems as well as the oil circulation between the contact surfaces can be improved by making radial and/or circumferential grooves on one of the contact surfaces [7]. The frictional behavior of such a wet cone clutch system has been studied from various viewpoints, from tribology [8] and lubrication engineering [9,10,11] to material science [12,13], heat transfer [14], solid and fluid mechanics [15,7,16].

The lifetime of wet cone clutch systems is mainly influenced by the wear of the friction surfaces, i.e., the clutch fails at a certain level of wear. The theoretical asperity based approach presented in [17] together with the experimental studies presented in [18] and [19] provide a wear model for wet cone clutches. Nevertheless, a well-accepted

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wear model of wet cone clutches incorporating the effect of lubrication regimes [17], temperature [18], and grooves has not been developed yet. This is one of the motivations of the present study.

The lifetime of the cone clutch friction materials can be improved by employing wear resistant coatings [20,21] and antiwear additive-containing lubricants [22,23]. Nevertheless, the wear of friction materials in the wet cone clutch systems can be further reduced by having control over the axial force applied on the clutch. Such an approach is one of the objectives of this work. The axial force produces a pressure between the two sliding friction surfaces which results in synchronization of the speed of the sliding surfaces. The axial force is normally provided by a hydraulic, pneumatic, or electromagnetic actuator and is conventionally kept constant or increasing during the synchronization process. Nevertheless, controlling the axial force of a wet cone clutch in a closed-loop configuration leads to a controllable friction torque and provides a precise control on the sliding speed and wear of the contact surfaces. Considering the advances in real time closed-loop control techniques as well as the actuator design, it is possible to have controllable actuators with high force and fast response [24,25,26].

An outstanding example of a wet cone clutch system is the synchromesh mechanism [27] used in various types of mechanical power transmission systems such as manual transmissions (MT), automated manual transmissions (AMT) and dual clutch transmissions (DCT) [4]. The main elements of a synchromesh system are illustrated in Fig. 1. Synchromesh (also known as Synchronizer) is located inside the transmission and makes the gear shifting smoother and easier. It consists of a wet cone clutch and a dog clutch system [6]. The gear shifting process starts with the engagement of the wet cone clutch and ends with the engagement of the dog clutch (blocking ring). The synchronization phase of the gear shifting process occurs during the engagement of the wet cone clutch system. Such a procedure is performed to synchronize the speed of the transmission main shaft and the speed of the gear being selected upon gear shifting [5,28]. A detailed theoretical analysis of the synchromesh was first given in the 1960s [29,30]. By developing simulation software as well as numerical analysis techniques, comprehensive experimental and theoretical studies [27] have been conducted on modeling and control of synchromesh operation with the purpose of controlling and improving the gear shifting process in MTs, AMTs [31,32,33], and DCTs, such as those performed by Walker and Zhang [4,34,35,36].

The case study here is a synchromesh wet cone clutch system as part of a clutchless 2-speed AMT designed for efficient gear shifting in an electric vehicle (EV) [37,38]. Such a clutchless electric powertrain [39,26,40] is designed with the purpose of improving the energy efficiency of electric vehicles (see Fig. 2) [41,42,43]. The high efficiency of AMTs and the high energy dissipation of the conventional dry clutch systems have turned the attention of EV manufacturers to clutchless AMT gear shifting [44,45,46,47]. The process of clutchless gear shifting in an AMT is performed by simultaneous control of the traction motor and the transmission. Due to the removal of the conventional dry clutch from the electric drivetrain, the absence of an efficient control on the cone clutch axial force results in a severe wear of the synchromesh

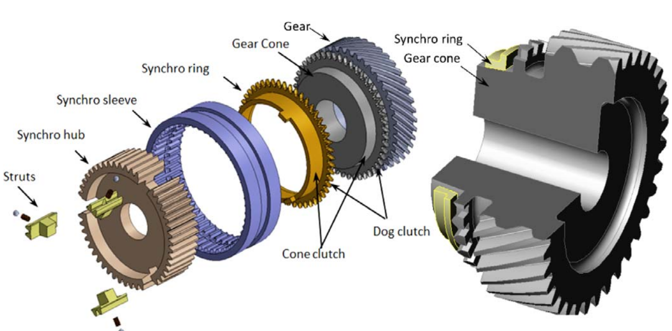


**Fig. 1.** Synchromesh main elements.

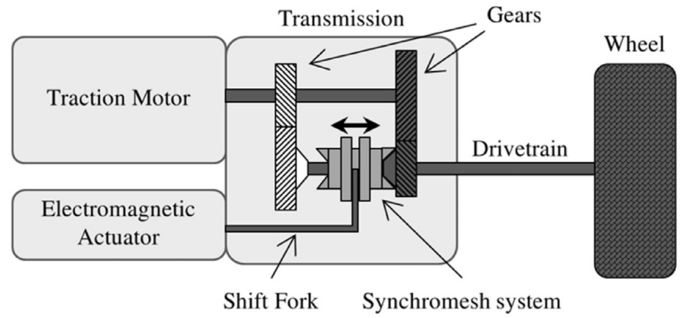


**Fig. 2.** Schematic diagram of an EV powertrain with an AMT equipped with an electromechanical gearshift system.

friction materials and drastically reduces the lifetime of the gear shifting system. Modelling the frictional and wear behaviour of the wet cone clutch and then controlling the synchronization process by considering the obtained models results in a new approach for controlling the synchromesh cone clutch [39]. This approach is the main motivation of the present work.

From a control point of view, considering the rapidity with which the cone clutch synchronization process occurs, a sufficiently simple controller is required to be implemented in real time to satisfy the performance objectives, and simultaneously perform the synchronization [48]. In this article, the performance objectives are defined to ensure satisfactory performance of the synchronization process over a short time scale, and to guarantee a sufficient service life over a longer time scale. The control approach developed in this paper provides a piecewise affine (PWA) feedback law. The PWA law is a reasonable choice for such an application since it is easy to implement in closed-loop real-time configuration [49,50]. The control design incorporates solving a linear programming (LP) problem in the offline phase to obtain the piecewise affine feedback which is then implemented in the real-time closed-loop control system [48,51,52]. A noticeable analogy exists between the presented controller design approach and the techniques used in the controlled invariance problem [53], reach control problems [54,52,55], and in-block controllability problem [56,57,58]. The control approach presented in this article has applications beyond the automotive industry and it can be extended to the frictional systems used in Robotics and Haptics [59,60].

In what follows, Section 2 discusses the regimes of lubrication involved in the cone clutch operation. Section 3 provides a model for the variation of the coefficient of friction during the synchronization process. Section 4 proposes a model to estimate the lifetime of cone clutch by considering the operating conditions. Section 5 analyzes the effect of temperature rise on performance and uncertainty. Section 6 formulates the cone clutch dynamical model. Section 7 develops the proposed PWA controller design, and discusses the robust stability proof and simulation results. Section 8 presents the experimental apparatus utilized to conduct the experimental investigations and experimental results. Section 9 concludes the paper. The main results of this paper are presented in Sections 7 and 8.

## 2. Cone clutch lubrication regimes

The coefficient of friction of the cone clutch is defined similarly to the definition of the coefficient of friction in dry clutches [7,10]. In particular,

$$f := \frac{T_f \sin\alpha}{F R_m} \tag{1}$$

Where $f$, $F$, and $T_f$ are the coefficient of friction of the cone clutch, axial force applied on the cone clutch, and frictional torque transferred through the cone clutch during the synchronization process, respectively. The clutch cone angle and mean radius are denoted by $\alpha$ and $R_m$,