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On the derivation of the pre-lockup feature based condition monitoring method for automatic transmission clutches

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ABSTRACT

This paper discusses how a qualitative understanding on the physics of failure can lead to a theoretical derivation of effective features that are useful for condition monitoring of wet friction clutches. The physical relationships between the features and the mean coefficient of friction (COF) which can be seen as the representation of the degradation level of a wet friction clutch are theoretically derived. In order to assess the accuracy of the theoretical relationships, Pearson′s correlation coefficient is applied to experimental data obtained from accelerated life tests on some commercial paper-based wet friction clutches using a fully instrumented SAE#2 setup. The analyses on the experimental data reveal that the theoretical predictions are plausible.

1. Introduction

Vehicles have become indispensable utilities in our modern society. Designs of vehicles have evolved from basic transportation utilities into advanced modern vehicles that can satisfy the increasing demands of the society for safety, driving comfort, high energy efficiency, low cost, high power capacity, *etc*. In a vehicle, a transmission system is one of the key devices that is responsible to accomplish the aforementioned requirements. A transmission system is defined as a device having the function to transfer power from the engine to the wheels, *via* the axles. The increasing sophistication of modern vehicles is also accompanied by the growing complexity of the transmission system.

In recent years, original equipment manufacturers (OEMs) have launched different types of transmission on the automotive market which can be, in general, classified into two main groups, namely (i) manual systems and (ii) semi or fully automatic system. A manual system consists of traditional Manual Transmission (MT), while the automatic system can be of different types, such as traditional Automatic Transmission (AT), Automated Manual Transmission (AMT), Continuously Variable Transmission (CVT), and Power Shift Transmission/Dual Clutch Transmission (DCT). As is obvious from its name, an automatic system is a transmission that shifts power or speed by itself, while the manual system involves the driver to do so.

Fig. 1 shows the annual sales ratios of manual and automatic systems with respect to the total annual sale of all transmissions from the years 2001 till 2015 [1,2]. The trends reveal that the drivers′ perspective has changed since the last decade. It is also obvious from the figure that the global economic recession occurring in 2008 and 2009 impacted the customers′ response on the selection of the transmission, which seemed to be only temporarily. Vehicles with manual

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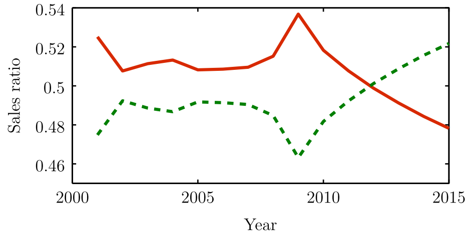

Fig. 1. Ratios of annual sales of manual systems (solid line) and automatic systems (dashed line) w.r.t the total annual sales of all kinds of transmissions on the global market.

systems have dominated the global automotive market for decades. However, the demand for the manual system is on the wane; and as predicted, the automatic systems will be dominating the global automotive market after the year 2012. This tendency is probably due to the fact that automatic systems offer more attractive capabilities that can satisfy the demands of our dynamic society, compared to the manual system [3].

Despite gaining popularity, there are some issues in automatic transmission systems that have been addressed and been attracting attention of many researchers across the world, namely energy efficiency improvement, emission reduction and driving performance enhancement. Modeling and simulation of the automatic systems have been carried out by many researchers in order to better understand the transmission behavior [4–7]. This understanding can serve as a basis for optimizing the transmission design and developing control strategies. Different advanced control strategies for automatic systems have been proposed in the literature, for example see Refs. [8–12], mostly focusing on improving fuel economy and enhancing gearshift quality.

Although considerable solutions related to the above-mentioned issues have been achieved, nevertheless, maintenance aspects were overlooked and they recently gain attention [13–16]. In fact, maintenance has also to be regarded as an important issue for the development of reliable automatic systems. An appropriate maintenance strategy on these transmissions is a necessity because of their vital function in the vehicles. While the complexity of automatic systems increases, the requirement for a maintenance strategy becomes more crucial. Undoubtedly, inevitable degradation occurring in the transmissions can change the vehicles′ performance. As the degradation progresses, failure can unexpectedly occur, which eventually leads to the total breakdown of the vehicles. Therefore, integration of a maintenance strategy into automatic transmission systems can significantly increase safety and availability/reliability and reduce the maintenance cost of the vehicles.

Condition Based Maintenance (CBM), which is also known as Predictive Maintenance (PdM), is a right-on-time maintenance strategy which is driven by the actual condition of the critical component(s) of any systems of interest. This concept requires technologies and experts, in which all relevant information, such as performance data, maintenance histories, operator logs and design data, are combined to make optimal maintenance decisions [17]. It has been realized that this maintenance strategy can significantly increase safety and availability/reliability and reduce the maintenance cost of systems of interest. PdM has been in use since 1980s and successfully implemented in various applications such as in oil platforms, manufacturing machines, wind turbines, automobiles, electronic systems [18–23].

In general, the key technologies for realizing the PdM strategy rely on three basic ingredients, namely (i) *condition monitoring*, (ii) *diagnostics* and (iii) *prognostics*. Condition monitoring (CM) aims at assessing the condition of a system/component of interest by means of tracking the change of a parameter that indicates a degradation progress. In the PdM research community, the parameter to be monitored is often referred to as a *relevant feature*. Diagnostics helps the maintenance engineer to localize and identify the fault type in a system/component. Finally, prognostics aims at predicting the remaining useful life (RUL) of a system/component at which the system/component will no longer perform its intended function. The RUL is estimated by means of forecasting the time interval needed by the feature to reach a pre-defined threshold that represents the end-of-useful life. Hence, (1) a *feature* to be monitored, (2) a *degradation model* which can be heuristically or physically derived, and (3) a *threshold* are critical aspects to succeed in development of the PdM strategy.

To realize the PdM strategy for automatic transmission systems, the critical component(s) therefore needs first to be identified. Afterwards, the condition monitoring, diagnostics and prognostics system for the critical component must be developed. For automatic transmission systems, wet friction clutches are one of the critical components. This consideration is based on the fact that the performance and long-term durability of such transmission systems are strongly determined by the clutch [24]. A brief introduction of wet friction clutches comprising the working principle and typical failure modes is discussed in Section 1.1.

1.1. Wet friction clutches and the failure mechanisms

Besides being used for automatic transmission systems, wet friction clutches are also widely used for limited slip differentials (LSDs) in all-wheel-drive (AWD) vehicles [25]. The LSD allows the AWD vehicles to have better maneuverability under severe road conditions. The forthcoming paragraphs only focus on the function, working principle of wet friction clutches that are widely employed in heavy duty transmissions such as ATs and DCTs.