

Experimental Characterization of Wet Clutch Friction Behaviors Including Thermal Dynamics

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ABSTRACT

Wet clutches are widely used in automotive systems. They are essential parts of automatic transmissions, modern All-Wheel-Drive systems or dual-clutch transmissions. Regardless of the area of application, a good knowledge of clutch friction behaviors is crucial for the clutch control system development. This paper considers two important factors of the wet clutch dynamics: coefficient of friction behavior and thermal dynamics. An Active Limited Slip Differential wet clutch with carbon fiber-based friction lining material is experimentally characterized by using a precise wet clutch setup. The characterization of the coefficient of friction behavior includes influence of clutch slip speed, applied force, and friction surface temperature. The clutch thermal dynamics is characterized based on the heat power balance law applied to the clutch separator plate with a variable heat transfer coefficient. The results of the thermal model experimental validation are presented, as well.

INTRODUCTION

Application of actively controlled wet clutches is growing in all segments of modern passenger vehicle power train systems. Traditionally they have been mostly used in automatic transmissions (AT). Today, they have become intrinsic parts of modern All-Wheel-Drive (AWD) systems with torque vectoring capabilities, where they are used as center differential couplings, or active elements in active or semi-active rear differentials. Another main field of their application includes high-torque dual-clutch

transmissions. Fig. 1 shows a schematic of a traditional wet clutch and outlines the main operating parameters.

Notwithstanding the area of application, an accurate clutch torque control is required, which necessitates a good knowledge of clutch friction characteristics. The friction characteristics are generally influenced by fluid type, friction lining material including surface roughness, clutch slip speed, applied force, friction interface temperature, and friction lining wear [1]. In the fields of AT research, where paper-based friction lining material is mostly used, the friction characteristics are commonly

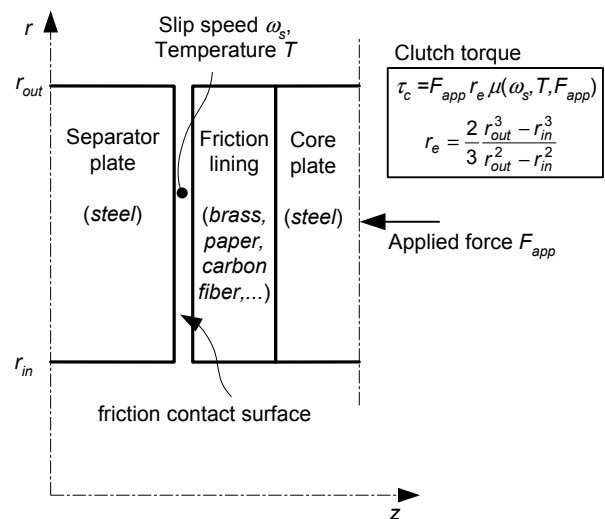
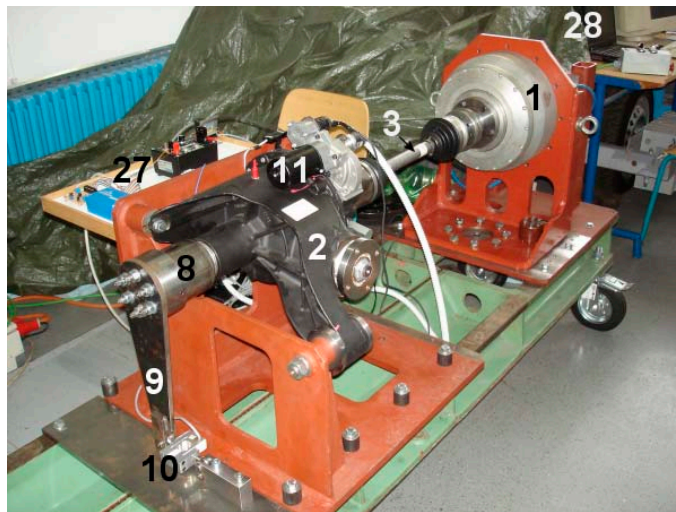
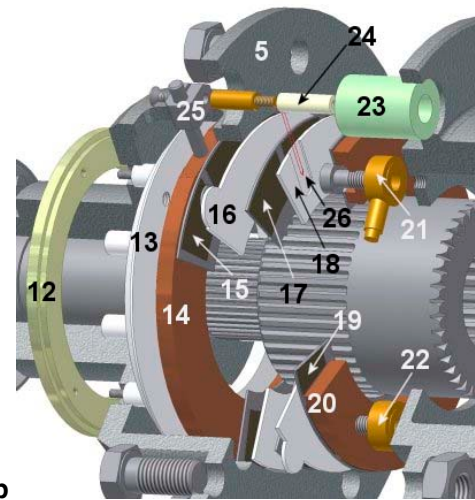


Figure 1: Schematic of traditional wet clutch (only one active friction surface is shown) with overview of operating parameters.



- a**
- | | |
|---------------------------------------|--------------------------------|
| 1 - Direct-drive electric servo motor | 13 - Press plate |
| 2 - Differential body | 17 - Friction disc |
| 3 - Input shaft | 16,18 - Separator plates |
| 5 - Differential case | 26 - 50 μ m Thermocouple |
| 9,10 - Torque measuring system | 15,19 - "Dummy" friction discs |
| 11 - Clutch actuator DC motor | |



- b**
- | |
|---|
| 20,21,22 - Axial force measuring system |
| 14,23,24,25 - Press plate position measuring system |
| 27 - Sensor amplifiers |
| 28 - Industrial Pentium III PC, electric motor power supply and control subsystem |

Figure 2: Wet clutch setup: (a) overview and (b) zoom-in detail of clutch exploded view

characterized by using SAE#2 machine [2]. For the purpose of friction characteristics identification of an Active Limited Slip Differential (ALSD) wet clutch with brass friction lining material, an experimental setup based on the specific ALSD hardware has been utilized in [3]. As part of the same research project activity, it has been shown that relatively simple, time saving, and inexpensive tests on pin-on-disc apparatus can provide results with good correlation when compared to the tests conducted by using wet clutch setup [4].

This paper presents experimental characterization of the frictional behavior of an ALSD wet clutch with carbon fiber-based friction lining material by using previously developed wet clutch setup (Fig. 2, [5]). It should be noted that the carbon-based friction material is relatively new and there is no evidence of published results on the related friction characteristics. The characterization is based on quasi-static experiments and includes influence of the following main clutch operating parameters: slip speed, applied force, and interface temperature.

From the standpoint of a control engineer, knowledge of the friction characteristics themselves is not enough. Accurate control of clutch torque control requires possibility of measurement or estimation of input operating parameters. In particular, the friction surface temperature is the parameter that requires real time estimation by using a model-based estimation approach. Namely, during wet clutch operation, a large amount of friction heat can be generated at the separator plate-friction lining interface. The heat is transferred partially through convection directly into the oil and partially conducted through the clutch components and then further transferred to the differential casing and to the oil.

This results in an increase of surface temperature¹ of the wet clutch friction material, which affects the clutch torque characteristics and limits the clutch thermal capacity. Therefore, a good insight in the wet clutch thermal dynamics and an existence of a simple and accurate thermal model are of big importance.

Description of the wet clutch thermal dynamics is, generally, a complex time-varying spatially-distributed problem. It is based on heat balance laws for the clutch components (separator plate, friction lining, and core plate – see Fig. 1) and a choice of appropriate boundary conditions. The solution can be obtained by time consuming finite element or finite difference methods [6-12]. Such an approach gives a good insight into temperature distribution in the whole clutch pack, and can be effectively utilized for optimization of the clutch components design and the choice of materials. However, this approach is not suitable for on-line temperature estimation due to model complexity, memory requirements, and computing inefficiency. Therefore, there exists a need for simple thermal models that can be easily experimentally parameterized and eventually provide acceptable modeling accuracy. In the available literature, such a modeling approach applied for AT wet clutch can be found in [13], for Torque Vectoring differential wet clutch in [14], and automotive dry clutch in [15]. The former one neglects the heat transfer at higher energies and temperatures and presents two simple models by considering only heat conduction in the separator plate. The second one considers a simple thermal energy balance with reference to the slip-power into clutch, the energy

¹ Note that in tribology, the time-dependent temperature rise due to frictional heating is referred to as the flash temperature [13].

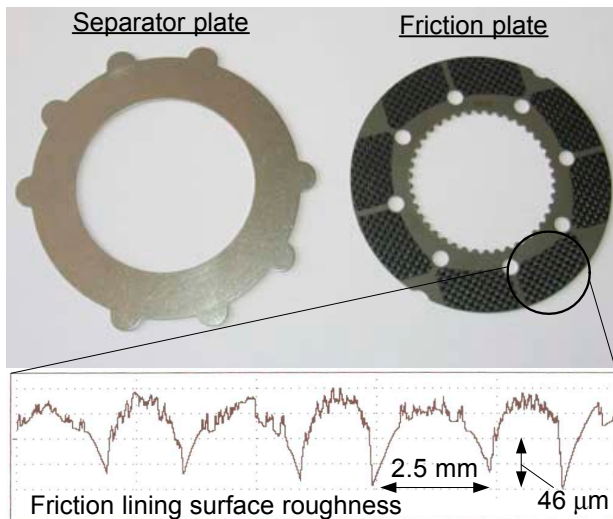


Figure 3: Separator and friction plate.

entering and exiting the system through lubrication, the slip-power dissipated directly into the oil, and the convective heat transfer between the clutch plates and the lubricant. The main applied assumptions are that 15% of the clutch slip power heats lubricant directly and that convective heat transfer coefficient from the plates to the oil is constant. The latter one presents a liner thermal model based on heat balance equations on the main clutch components and considers all main heat transfer mechanisms in a way of lumped parameter-based approach. The model structure provides relatively easy parameter identification.

This paper presents a pragmatic semi-physical approach of wet clutch thermal dynamics modeling. It is based on thermal energy balance applied to the separator plate. The main difference when compared to [14,15] is that the heat transfer is described by a single parameter that encompasses all existing heat transfer mechanisms. The experimental identification of the generalized heat transfer coefficient is conducted in detail with respect to change of the operating parameters. Both static and dynamic heat transfer behaviors are considered. The model is experimentally validated.

EXPERIMENTAL SETUP

The experimental work has been conducted on a precise wet clutch experimental setup based on an ALSD hardware with electromechanical clutch actuator [5]. Fig. 2 shows a photograph and a 3D CAD drawing of the setup. It includes one friction plate placed between two separator plates. The clutch is actuated electromechanically by means of a geared DC motor connected to a ball-ramp mechanism that converts rotation into linear motion. The clutch is driven by a torque servomotor providing a precise closed-loop control of the clutch slip speed. The measured variables are the clutch torque, the actuator motor position and the armature current, the clutch applied force, the separator

plate temperature, the press plate axial position, and the oil sump temperature. More details about the setup and the measuring equipment can be found in [5].

FRICITION BEHAVIOR CHARACTERIZATION

FRICITION PAIR DESCRIPTION - The wet clutch considered in this work comprises a separator plate made of hardened steel with the roughness $R_a = 0.31 \mu\text{m}$ and a friction plate with carbon fiber-based friction lining material (see Fig. 3). The friction lining material is made of woven carbon fabric to which a phenolic resin has been applied [16,17]. Such materials have an open area texture for fluid flow and microporosity or microstructure for destruction of any potential hydrodynamic films in order to prevent undesired effects at low sliding speeds such as shudder, squawk, or chugle. At the same time this material provides an extremely strong and durable structure. Standard oil for the Active Limited Slip Differential application was used (Castrol 75W-140).

DESIGN OF EXPERIMENT – Friction characteristics are traditionally obtained through a series of static experiments where operating parameters (slip speed, interface temperature, and applied force) are controlled at preset values. This approach requires possibility of control of all the operating parameters. The wet clutch setup provides control of the slip speed and the applied force. The interface temperature is measured by a thermocouple placed in one of the separator plates². The preliminary experiments have shown that the interface temperature cannot be easily controlled. A fast dynamics of the temperature change have been observed during experiments, which is mainly influenced by a very small mass of the separator plate. Therefore, the approach based on static experiments is not suitable for the particular case. In order to avoid the outlined difficulties a quasi-static experiment-based approach has been applied in this work. That approach is also less time-consuming.

Fig. 4 shows experimental recordings of a typical experiment. The friction interface is firstly heated up to a preset initial temperature. During heating, the slip speed and applied force are kept constant. When the preset interface temperature is reached, the slip speed is decreased slowly down to zero slip speed in the time of 10 seconds. During that period the interface temperature freely changes influenced by clutch thermal dynamics. The change of interface temperature with respect to slip speed in the demonstrated experiment is shown in Fig. 5 denoted by red arrows. In order to cover a full range of interface temperatures and slip speeds, the initial temperature and the initial slip speed were varied, as demonstrated in Fig. 5.

² It is assumed here that the friction interface temperature is equal to the steel separator plate temperature, which is justifiable because the separator plate has very small mass and is made of steel which is characterized by high thermal conductivity. The temperature is measured at the separator plate mean radius.