

Design of Test Rigs for a Dry Dual Clutch and its Electromechanical Actuator

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ABSTRACT

Dual Clutch Transmissions with dry electromechanically actuated clutches have emerged on the market recently. In order to provide their favorable operation in terms of the clutch torque control, it is very important to have a good knowledge on the system behavior related to the actuator dynamics, the dry friction coefficient behavior, and the thermal dynamics. This paper describes two test rigs developed to support the research work on a dry dual clutch with a lever-based electromechanical actuation system. The first test rig (actuation system test rig) provides a basis for a comprehensive multi-step identification of the actuation system parameters and characterization of the overall system behavior. This test rig includes a modified dual clutch assembly including a built-in sensor for the purpose of direct normal force measurement. The second test rig (transmission test rig) is aimed at providing support for more comprehensive characterization of the actuation system under realistic operating conditions and characterization of the clutch torque transfer dynamics/friction coefficient behavior, thermal dynamics, and wear. Both test rigs are computer controlled and include measurements of all main system variables. Functionality of the test rigs is demonstrated by characteristic experimental results.

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INTRODUCTION

Dual clutch transmissions (DCTs) enable the delivery of the fuel efficiency of a manual gearbox with the convenience and ease of a premium automatic transmission [1]. They can be implemented either with multi-plate wet or single-plate dry clutches. The wet clutch-based versions are well established on the market (e.g. [2,3]), while the dry clutch-based opponents have recently emerged on the market introduced by VW, Ford, Renault, and Hyundai (e.g. [4,5]). Compared to the wet dual clutches, practical application of dry dual clutches is generally limited to smaller vehicles due to potential issues regarding the stability of dry friction characteristics, the thermal capacity, and durability [6]. In terms of the clutch actuation mechanism, electrohydraulic [4,7] or electromechanical leverbased systems [8] are utilized. Alternative solutions, such as moving magnet linear or elastic lever-based electromechanical actuator mechanisms, are also being considered for practical implementation [6]. When compared to the electrohydraulic actuation systems, the lever-based electromechanical solution

may provide easier integration in the whole transmission system and potentially better total energy efficiency [8,9,10,11]. However, operation of such a system may be largely affected by the system friction and compliance, the components' misalignment, and the driving motor dynamics.

DCT shift control relies on the coordination between the two clutches, where one clutch is being opened (off-going clutch) and the other activated (on-going clutch) (e.g. [1]). During torque transfer in the actual gear, the clutches may operate in constant slipping mode with low slip speed in order to improve NVH performance [12]. This mode may be challenging in terms of robust control in the presence of an unstable friction characteristics or nonlinear effects in the actuator system (friction hysteresis or delay). During vehicle launch, the forward clutch is controlled in order to provide accurate tracking of the desired slip speed [12]. Disregarding the operating mode, availability of an accurate clutch torque control for both clutches is of great importance. In order to provide this, it is highly desired to have a good knowledge of the system behavior in terms of the actuator dynamics, the

friction coefficient behavior, and the thermal dynamics. This can be provided through proper experimental characterization procedures. To the author's best knowledge, the available literature dealing with characterization, modeling or control of the lever-based electromechanical actuators for dual clutches, the clutch mechanism dynamics, and the dry clutch friction coefficient behavior, the dry clutch thermal dynamics or the wear is rather limited (e.g. [13,14,15,16,17,18]). This paper describes test rigs for an electromechanically actuated dry dual clutch aimed at supporting these research activities. The first test rig is intended for characterization of the actuation system dynamics. The second test rig is aimed for further, more comprehensive characterization of the actuation system under realistic operating conditions and characterization of clutch torque transfer dynamics/friction coefficient behavior, thermal dynamics, and wear. Detail description of the test rigs is accompanied by experimental results used to validate the functionality of the test rigs functionality and demonstrate some of the basic features of system behavior.

SYSTEM DESCRIPTION

Fig. 1 shows schematic representation of the clutch system. The flywheel along with the pressure plates is connected with the engine output. Torsional leaf springs provide connection between the flywheel and the pressure plates. They transmit torque between the components and at the same time represent the clutch return springs allowing for consistent clutch opening and closing during disengagement and engagement process, respectively. The torque delivered by the engine is transmitted to the transmission input shaft through two separate clutch disks with dry friction material. Each disk is connected with the corresponding transmission input shaft through spline fitting that provides torque transfer while allowing for the relative axial displacement during the clutch engagement process. As in traditional dry clutches, the clutch disk core plate, so-called cushion plate, is realized as multiple elastic circumferentially-woven thin metal plate segments attached to the center plate that is attached to the transmission input shaft through spline fitting. The elastic core plate provides uniform contact between the friction linings and the mating surface, i.e. the pressure plate or the flywheel.

The clutch torque capacity/normal force is controlled through the lever (diaphragm) springs (see Fig. 1). Input and output sides of each lever spring are connected with the corresponding engagement bearing and the pressure plate, respectively. The lever spring balances torques related to its reactive torque and torques produced by the engagement bearing force, the clutch normal force, and the clutch return springs with respect to the lever spring fulcrum. The lever spring fulcrum is a part of a clutch wear compensation mechanism, which maintains a constant clutch axial clearance in order to provide a proper and a robust clutch actuation control. The wear compensation mechanism is purely mechanical system consisting of plurality of wedges, spring,

and limiters. Detail description of operation of this system is beyond the scope of the paper.

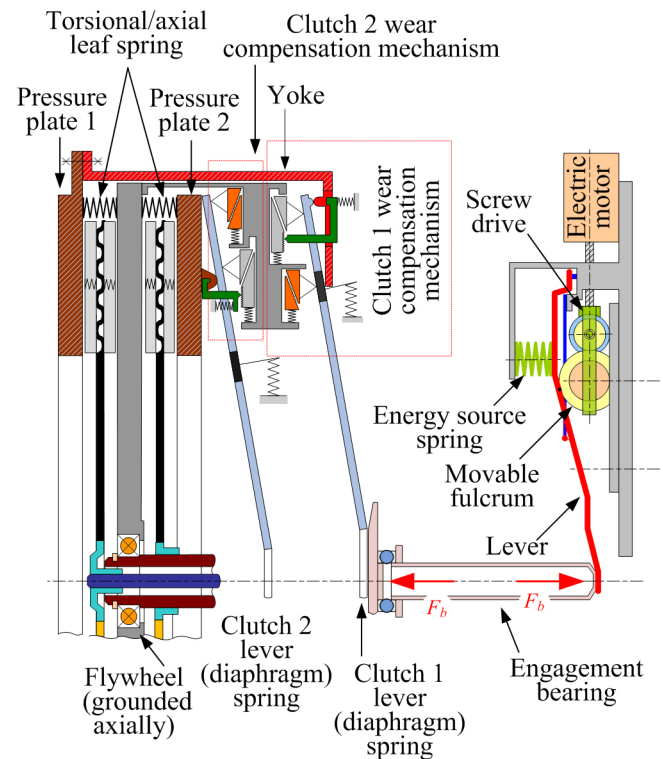


Figure 1. Illustration of dry dual-clutch with lever based electromechanical actuator.

The engagement bearing force is controlled by the lever-based electromechanical actuator. The driving electric motor drives the lever fulcrum through a ball-screw drive mechanism. The actuator lever balances torques produced by the preloaded energy storage spring force and the engagement bearing force with respect to the movable fulcrum. In this way, the engagement bearing force, i.e. the clutch normal force, is controlled by changing the lever arms associated with the actuator lever fulcrum position. More details on the actuator system and its modeling can be found in [19].

ACTUATION SYSTEM TEST RIG

The actuation system test rig has been developed in order to provide a basis for a comprehensive multi-step identification of the actuation system parameters and characterization of the overall system behavior. Two configurations have been proposed in order to provide separate characterization of lever actuator system (Configuration 1) and dual clutch assembly and overall actuation system (Configuration 2).

MECHANICAL AND MEASUREMENT SYSTEM - CONFIGURATION 1

Fig. 2 shows schematic and photograph of the actuator test rig in Configuration 1. The rig has been built around the original clutch bell housing that accommodates the actuators and their driving motors. The characterized actuator is loaded by a linear helical compression spring in order to avoid influence of the dual clutch assembly nonlinear effects. For the purpose of tests, springs with three different stiffness coefficients were used. The spring provides comparable magnitude of load as the real dual clutch. In order to simulate different loading conditions, an adjustment mechanism is added in order to provide manual variation of the spring preload or the clearance between the engagement bearing and the loading spring. The engagement bearing force is directly measured by a precise strain-gauge force sensor (HBM, type S-9, accuracy class 0.05). The lever motion is measured by using two LVDT (Linear Variable Differential Transducer) displacement sensors (Omega, LD320-10, measuring range: $\pm 2.5 - \pm 150\text{mm}$, linearity: $<0.2\%$). One is used to measure the lever output/engagement bearing displacement, while the other is used to measure the displacement of the opposite side of lever at the support point (see Fig. 1).

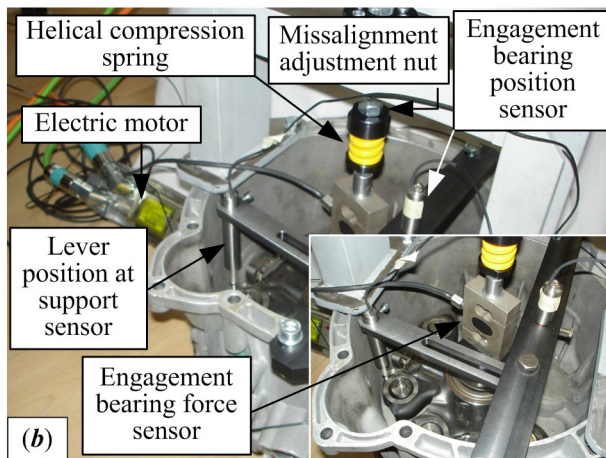
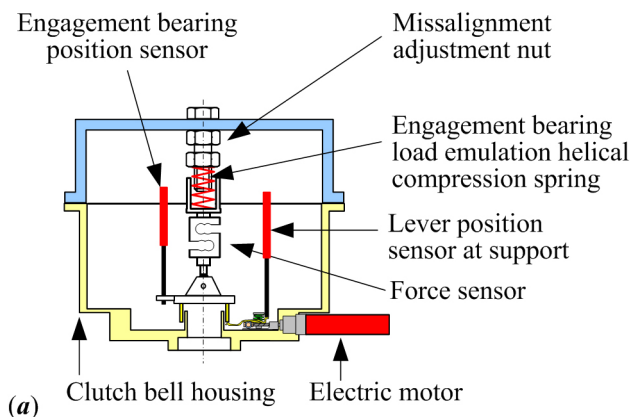


Figure 2. Clutch actuator test rig in Configuration 1: schematic (a) and photograph (b).

MECHANICAL AND MEASUREMENT SYSTEM - CONFIGURATION 2

Fig. 3 shows schematic and photograph of the actuation system test rig in Configuration 2. The configuration is aimed for characterization of (i) the actuator with realistic loading conditions provided by the dual clutch and (ii) the dual clutch axial dynamics.

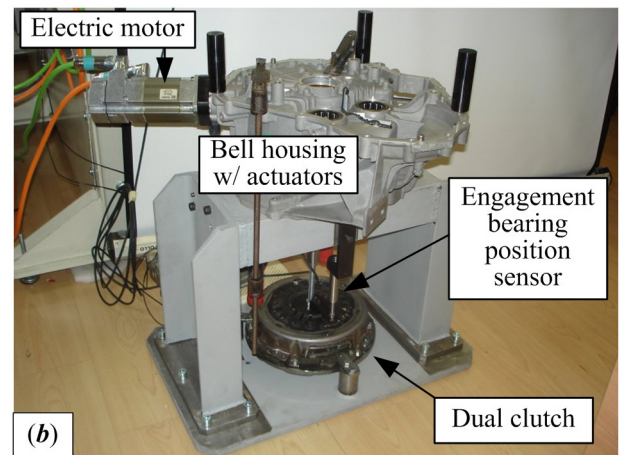
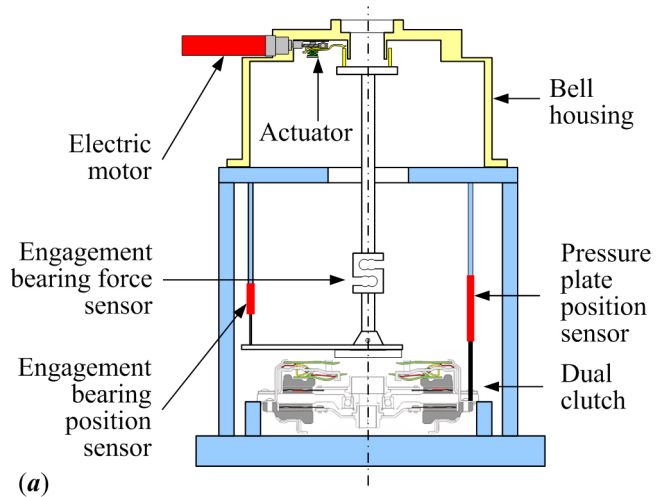


Figure 3. Clutch actuator test rig in Configuration 2: schematic (a) and photograph (b).

In order to accommodate the engagement bearing force measurement, the two subsystems are axially displaced and connected by means of the same strain gauge sensor used in Configuration 1 and appropriate custom made fixing elements for each actuator/clutch pair. Two LVDT displacement sensors (Omega, LD320-10, measuring range: $\pm 2.5 - \pm 150\text{mm}$, linearity: $<0.2\%$) are used to measure the engagement bearing position and the pressure plate position.

In order to provide more direct insight into the clutch axial dynamics behavior, the flywheel has been modified to provide normal force measurement as illustrated in Fig. 4a. The normal force is sensed by measuring a reaction force in one of three supporting points of a custom made clutch