Mechatronics 21 (2011) 501–508

Contents lists available at ScienceDirect

Mechatronics

journal homepage: www.elsevier.com/locate/mechatronics

A two-level Iterative Learning Control scheme for the engagement of wet clutches

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ARTICLE INFO

Article history:
Received 17 August 2010
Accepted 11 January 2011

Keywords:
Iterative Learning Control
Control scheme development
Wet clutch
Piecewise systems
Trajectory optimization

ABSTRACT

This paper discusses the application of Iterative Learning Control (ILC) algorithms for the engagement of wet clutches. A two-level control scheme is presented, consisting of a high level ILC-type algorithm which iteratively updates parameterized reference trajectories which are tracked by the low level tracking control. At this low level, two standard ILC controllers are used to first track a pressure reference in the filling phase and afterwards a slip reference in the slip phase of the clutch engagement. The performance and robustness of the presented approach are validated on an experimental test setup. It is shown that both levels are crucial to achieve good engagement quality during normal machine operation. Through the use of this ILC control scheme, it is possible to avoid time-consuming and cumbersome experimental (re)calibrations, which are nowadays used to achieve and maintain good performance despite the complex and time-varying dynamics of wet clutches.

1. Introduction

Wet clutches are mechanical devices used to transmit torque from their input shaft to their output shaft by means of friction. They are used in various types of automatic transmissions to selectively engage gear elements. By disengaging one clutch and engaging another, different transmission ratios can be realized. Wet clutches are also used for off-road vehicles and agricultural machines where high torques are transmitted. These vehicles typically operate under varying environmental conditions and the clutches wear out over time [1]. In addition to this time-varying behavior, the dynamics of clutches are highly non-linear [2]. Operators however always expect a fast and smooth response without drivetrain jerking, so without oscillations induced due to a poor engagement. These expectations combined with the varying and non-linear clutch dynamics make wet clutch control a challenging industrial problem [3]. Current industrial controllers use parameterized feedforward signals that are experimentally calibrated. To cope with the varying dynamics the signal parameters are regularly recalibrated during machine servicing. In an attempt to avoid this downtime, various patents have been claimed that describe empirical rules for adjusting the signal parameters during normal machine operation, based on observations of past engagements [4–6]. In this paper, a control scheme based on Iterative Learning Control (ILC [7,8]) is presented as an alternative, efficient strategy to learn and adapt the control signals during normal machine operation without the need for recalibrations.

A schematic cross-section of a wet clutch is shown in Fig. 1. Its input shaft is connected to a hollow cylinder with internal grooves, called the drum. A first set of friction plates (clutch plates) with external toothing can slide in those grooves, while a second set of friction plates (clutch discs) with internal toothing can slide over a grooved bus connected to the output shaft. Torque is transferred between the shafts by pressing both sets together with a hydraulic piston, realized by sending a control signal to the servovalve in the hydraulic line to the clutch. When this is done, the clutch chamber first fills up with oil and the pressure builds up until it is high enough to compress the return spring and move the piston towards the friction plates. This is called the filling phase, and it ends once the piston advances far enough and presses the plates together such that torque transfer commences. At this moment the slip phase begins and the system dynamics change considerably, yielding strongly non-linear system behavior. The difference in rotation speeds between the in- and output shafts, denoted the slip, then decreases until both shafts rotate synchronously. A good engagement is obtained when torque transfer starts as soon as possible without introducing torque peaks, which can be realized by a short filling phase and a smooth transition into the slip phase. This control problem is further complicated by the fact that the piston position is generally not measured on industrial machines. Only pressure sensors measuring the pressure in the line to the clutch and encoders measuring rotational speeds of the in- and output shafts of the clutch are available.

Several authors have derived full physical models for wet clutches [2,9–14]. These have been applied to the design of feedback controllers in [2,10] and feedforward controllers in [11,12]. This requires a large effort to get accurate models, typically

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doi:10.1016/j.mechatronics.2011.01.002

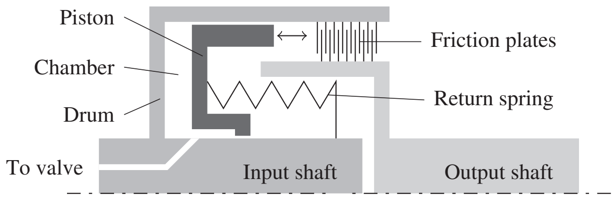

Fig. 1. Schematic representation of a wet clutch and its components.

consisting of white box modeling in combination with experimental parameter estimation. Complex models also complicate control design and often result in complicated control structures, unless simplified models are used, as in [2,14]. Using separate controllers for the filling and slip phases can make things easier as well, as it now suffices to develop a model for each phase separately. However, the transition between both controllers now becomes crucial and a large amount of tuning is often needed in order to get good results. This technique is employed in [9,15], where a feedforward signal is used to bring the clutch into the slip phase, before feedback controllers are activated to regulate slip or pressure respectively.

An aspect that is generally paid little attention during the control design is the large variation in the operating conditions and the clutch behavior. For a practical implementation, either further effort is required to include this variation in the model or the controllers have to be tuned online to ensure the performance is maintained.

Learning is a technique that has been extensively used to control repetitive tasks. ILC [7,8] is considered as a means of improving the tracking accuracy without compromising the robustness, even when faced with large model uncertainty. The model can even be omitted entirely, as in [16]. A learning approach has also been applied to optimize the parameters of feedback controllers automatically, as in [17,18], thereby avoiding the need for good models during the design process, and of feedforward controllers, as in [19]. However, as already stated in [16], most of these learning techniques require the availability of reference trajectories. Since no position measurement is available tracking based control techniques can therefore not be used directly. Instead of opting for machine learning techniques [20], we therefore propose to use a two-level control scheme, learning good reference trajectories at the high level for indirect but measured variables, while ensuring they are tracked accurately by low level ILC controllers. Like in [9,15], the filling and slip phase are controlled separately, with the low level consisting of one ILC controller for each phase. The high level contains ILC-type learning algorithms that use the obtained performance to adapt the reference trajectories, which are initially unknown and vary with the operating conditions.

The remainder of the paper is organized as follows: In Section 2 the basics of ILC are first explained. Next, the general control scheme is discussed in Section 3, while Sections 4–6 discuss the low and high level implementations. Section 7 presents an experimental validation for clutch engagements. Section 8 finally concludes the paper and presents some suggestions for future work.

All experiments are carried out on the dedicated test bench shown in Fig. 2. It consists of an AC electromotor (30 kW), controlled to a constant velocity by a high bandwidth motor drive. The output shaft of this motor drives a primary transmission via a torque converter. In this transmission, the forward clutch remains engaged while the proposed control scheme is utilized to control the first range clutch. When engaged, it transfers power to the load, which consists of a flywheel (2.5 kg m^2) connected through a secondary transmission. This makes it possible to vary the inertia observed by the controlled clutch. The transmission to be controlled is equipped with several sensors, measuring the speeds of the different shafts and the pressure of the oil in the line to the clutch. An additional sensor is installed to measure the transferred torque, but this sensor is only used for illustrative purposes, not for the control itself. A dSPACE 1103 control board is used to run the controller and to drive the servovalve current. Also note that the slip is normalized within the range of 1–0, with 1 corresponding to the output shaft at standstill and 0 corresponding to the output shaft at synchronous speed.

2. Iterative Learning Control

The main idea in ILC is to improve the tracking performance of repetitive systems using the results of previous iterations [7,8]. Fig. 3 shows the first-order ILC control scheme, where y is the output of the plant and r is an iteration independent reference trajectory. The ILC control signal for the $(i+1)$th iteration, u_{i+1}, is calculated based on the previous ILC control signal, u_i and the previous tracking error e_i. In this paper a linear update law is chosen such that

$$u_{i+1}(k) = Q(D)(u_i(k) + L(D)e_i(k)), \tag{1}$$

with D the delay operator, and Q and L linear operators that can be chosen during the design of the ILC controller. For this update law, a frequency domain criterion for monotonic convergence can be derived, as well as a frequency domain expression for the remaining error after convergence [7,8]. For a plant with frequency response function (FRF) $P(\omega)$, the controller (1) yields a monotonically decreasing tracking error if

$$|Q(\omega)(1 - L(\omega)P(\omega))| < 1, \tag{2}$$

with $Q(\omega)$ and $L(\omega)$ the FRF's of the operators Q and L. After convergence, the remaining error $E_\infty(\omega)$ is given by:

$$E_\infty(\omega) = \frac{1 - Q(\omega)}{1 - Q(\omega)(1 - L(\omega)P(\omega))} R(\omega), \tag{3}$$

where $R(\omega)$ is the Fourier transform or the reference r.

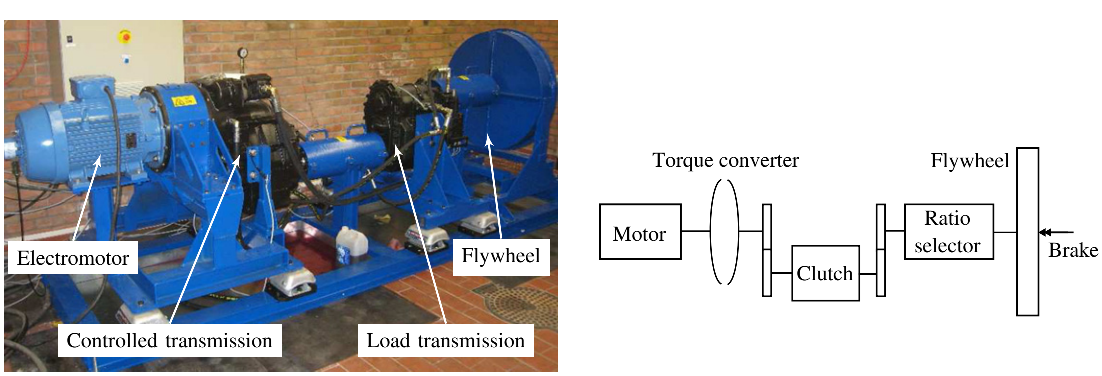

Fig. 2. Test bench consisting of an electromotor driving a flywheel via two mechanical transmissions: one transmission with the controlled clutches, the other transmission is used to vary the observed load and to adjust the braking torque.