Mechanical Systems and Signal Processing 24 (2010) 1924–1937

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

journal homepage: www.elsevier.com/locate/jnlabr/ymssp

Iterative learning control for the filling of wet clutches

G. Pinte [a,*], B. Depraetere [b], W. Symens [a], J. Swevers [b], P. Sas [b]

[a] FMTC, Celestijnenlaan 300 D, B-3001 Leuven, Belgium
[b] Department of Mechanical Engineering, Celestijnenlaan 300 B, B-3001 Leuven, Belgium

ARTICLE INFO

Article history:
Received 19 May 2010
Accepted 20 May 2010
Available online 26 May 2010

Keywords:
Wet clutch
Filling phase
Clutch engagement
Iterative learning control
Position control
Pressure control

ABSTRACT

This paper discusses the development of an advanced iterative learning control (ILC) scheme for the filling of wet clutches. In the presented scheme, the appropriate actuator signal for a new clutch engagement is learned automatically based on the quality of previous engagements, such that time-consuming and cumbersome calibrations can be avoided. First, an ILC controller, which uses the position of the piston as control input, is developed and tested on a non-rotating clutch under well controlled conditions. Afterwards, a similar strategy is tested on a rotating set-up, where a pressure sensor is used as the input of the ILC controller. On a higher level, both the position and the pressure controller are extended with a second learning algorithm, that adapts the reference position/pressure to account for environmental changes which cannot be learned by the low-level ILC controller. It is shown that a strong reduction of the transmitted torque level as well as a significant shortening of the engagement time can be achieved with the developed strategy, compared to traditional time-invariant control strategies.

1. Introduction

A wet clutch is a mechanical device that transmits torque from its input axis to its output axis by means of friction. Wet clutches are often used in power transmissions of off-road vehicles and agricultural machines to selectively engage gear elements. These vehicles are operating under varying environmental conditions, e.g. different temperatures in winter and summer. Moreover, these vehicles are also used during several years such that the clutches are subject to a significant amount of wear and their dynamics will change over time. As a consequence of these varying conditions and system dynamics, the control signals for wet clutches leading to an optimal engagement change drastically during the transmission's life cycle and the control action should therefore be adapted accordingly. In [1], the robust control of wet clutches is identified as a challenging industrial control problem. Much research has been carried out in this field in the past two decades and numerous patents have been generated [2–5]. In this paper, iterative learning control (ILC [6]) is presented as an alternative, efficient strategy for the control of wet clutches, which can find the appropriate control action despite the varying system dynamics and environmental conditions.

Fig. 1(a) shows the design of a wet clutch. The input axis of the clutch is connected to a drum, which is a hollow cylinder with grooves on the inside. 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 axis. An electro-hydraulic pressure-regulated proportional valve regulates the pressure inside the clutch with the objective to

* Corresponding author. Tel.: +32 16 328035.
E-mail address: gregory.pinte@fmtc.be (G. Pinte).

0888-3270/$ - see front matter
doi:10.1016/j.ymssp.2010.05.016

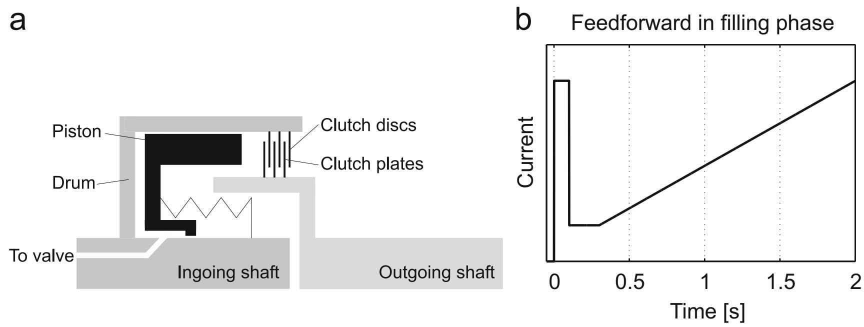

Fig. 1. A wet clutch: (a) the mechanical design and (b) the typical feedforward current signal to the electro-hydraulic valve in the filling phase.

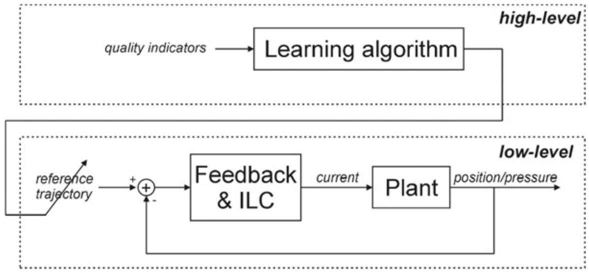

Fig. 2. The applied two-level control scheme with a low-level ILC controller and a high-level learning algorithm to update the reference of the low-level controller.

control the displacement of a piston which can press the two sets of friction plates together such that torque is transmitted. Initially, when the clutch is not engaged, the piston should be positioned as far as possible from the friction plates to avoid energy losses due to viscous friction of the oil between the plates. If the clutch is not hydraulically actuated, a return spring keeps the piston in this position. When the vehicle control unit gives the command to engage the clutch, the clutch is filled with oil in preparation of the effective engagement. The objective is to decrease the distance between the piston and the plates as fast as possible to zero, without the piston and the plates making brutal contact. This first phase in the engagement of a wet clutch is referred to as the filling phase. Afterwards, when the oil pressure is further increased, the friction plates are pressed together and torque is transmitted through the clutch. However, there is still a rotational speed-difference between the input and output shaft, resulting in energy dissipation in the clutch. A slip controller in this phase can be used to improve the quality of shifting [8]. Finally, when the oil pressure inside the clutch exceeds a certain level, the clutch will be fully engaged. The complete torque is transmitted through the clutch and the clutch is not slipping.

In this paper, the control of the filling phase of wet clutches is studied. Nowadays, wet clutches in industrial transmissions are filled using a feedforward controller of the current to the electro-hydraulic valve, which regulates the oil pressure and hence the piston position in the clutch. Fig. 1(b) shows a typical parameterized, feedforward current signal, which is sent in the filling phase to the valve [2]. Although nowadays more advanced feedforward signals with more tunable parameters are sometimes applied [4], the above-mentioned parametrization perfectly illustrates the underlying idea behind the actual industrial control design. First, a current pulse is sent to the valve in order to generate a high pressure level in the clutch. This way, the piston will overcome the preloaded return spring and start to accelerate towards the friction plates. After this pulse, a lower constant current is sent out in order to decelerate the piston and position the piston near the friction plates. Finally a growing ramp current signal is sent to the valve such that the pressure in the clutch gradually increases and the clutch smoothly engages. The duration of the current pulse and the constant current level afterwards are critical to achieve a good filling and a smooth start of the engagement process [1]. On the one hand, a very long current pulse leads to an overfilling of the clutch such that the piston suddenly makes brutal contact with the friction plates resulting in undesired high peaks in the transmitted torque. On the other hand, a very short current pulse or a very low constant current level after the pulse leads to an underfilling of the clutch, resulting in a very slow engagement. To avoid over- and underfilling, in many industrial vehicles long calibration procedures are applied to find the optimal parameters of the feedforward current signal (i.e. the optimal combination of the pulse duration and constant current level) for a smooth clutch engagement. Furthermore, since the controlled system is time-varying, as described above, regular recalibrations of these parameters are inevitable. To avoid these cumbersome calibrations, some patents [5,2] describe adaptive algorithms to update the current pulse parameters at each filling of the clutch, based on the velocity and acceleration of the input and output shaft in the previous clutch engagement.

This paper presents a two-level control system for the filling of wet clutches (Fig. 2), which does not update the discrete parameters of a predefined, feedforward current signal but determines a continuous current signal to the valve for a new