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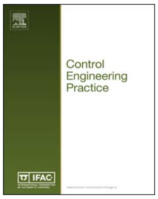

# Multivariable control of a test bed for differential gears

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## ABSTRACT

Common problems related to the control of power train test beds are the coupling of the two typical controlled variables rotational speed and testing torque as well as resonant torque oscillations. This work presents a simplified non-linear mathematical model of a test bed for differential gears including the unit under test suitable for controller design. Based on this system model, a new control concept with input–output decoupling and feedback linearisation is developed to overcome both previously mentioned problems. Simulation studies using the proposed control structure as well as a conventional control concept for power train test beds show the superiority of the new controller.

Finally the proposed controller was implemented on real-time processing hardware and tested on a commercial test bed for differential gears to prove the performance of the new control concept in practice.

## 1. Introduction

Test beds have become an integral part of development processes in the automotive industry. Reduced development time, reduced cost and better reproducibility of test runs are just some of the many advantages of using test beds (Goos, 2013; Kokalj, Lewis, & Zach, 2012; Pillas, Kirschbaum, Jakobi, Gebhardt, & Uphaus, 2014). While vehicle test beds such as chassis dynamometers or Road-to-Rig (R2R) test beds (Bauer, 2011) are typically applied to analyse the entire vehicle or at least the complete power train, another class of test beds is used to test single power train components. These power train test beds are used in the development process of various types of gearboxes, differentials or clutches to perform function tests, fatigue and endurance tests, efficiency tests or to analyse the Noise Vibration and Harshness (NVH) behaviour. These automotive components are usually tested individually; the vehicle's remaining power train has to be emulated by software and electric drives so that the testing conditions are close to the loads arising in typical driving manoeuvres.

Although testing a differential gear is quite different from testing a gearbox or a dog clutch, the control related aspects are similar. Typically, the main requirement is the control of the electric drives to track the reference signals for testing rotational speed and testing torque. As power train test beds are multivariable dynamic systems, these two system outputs are always coupled (Bunker, Franchek, & Thomason, 1997) and independent control of rotational speed and torque is challenging. Furthermore, due to potentially low internal damping in the mechanical structure, special focus has to be placed on the damping of resonant torque oscillations.

Although power train test beds are a very common tool in the automotive industry there is not much research work available dealing with the control of these test beds. Ibendorf (2008) is one of the few publications on designing and controlling power train test beds. However, there are similar challenges in the control of engine test beds. Here the two controlled variables are engine speed and engine torque while the actuators are the internal combustion engine (ICE) and the dynamometer. One control strategy often used in practice is to use proportional-integral-derivative (PID) controllers to control ICE and dynamometer individually. Typically, first the speed control loop is closed, then the torque controller can be designed to reach acceptable closed loop dynamics (Bunker et al., 1997). This is also the conventional control concept for power train test beds. With this strategy the control performance might be satisfying in steady-state, but rotational speed and torque are still coupled in dynamic operation. Therefore, most recent approaches for controlling engine test beds are based on multivariable control to reduce the interactions of speed and torque control loop.

For example in López, Espinosa, and Agudelo (2011), two

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separate proportional-integral (PI) controllers are used to control rotational speed and torque but each control action passes through a decoupling network and physically acts on both ICE and dynamometer to decouple rotational speed and torque. However, the authors neglected the torsional flexibility of the shaft connecting ICE and dynamometer and thereby resonance phenomena. In Bunker et al. (1997), a decoupling controller based on balancing the bandwidths of the two control loops with a special focus on robustness was presented, but the flexible shaft was not considered either. In Passenbrunner, Sassano, and del Re (2011), the test bed was modelled as a two-mass oscillator, including the torsional flexibility. Optimisation based control was then used to simultaneously control engine speed and torque. Further alternative control concepts are presented in Priesner, Westermayer, Jakubek, and Bauer (2012) and Gruenbacher and del Re (2008).

Some of these ideas can be applied to control a power train test bed, but there are some important differences: instead of the highly non-linear ICE with possibly uncertain dynamic behaviour, an electric drive with well-known torque dynamics, which is usually easier to control, is used. This typically results in less dead time and a faster torque control loop. Additionally, the complexity of the mechanical system increases when the simple connecting shaft used on the engine test bed is replaced by a complex power train component such as a gearbox. In addition to engine test beds, other applications typically requiring decoupled control are steel processing lines (Jeon, Kim, Jung, Sul, & Choi, 1999), paper machines (Valenzuela, Bentley, Aguilera, & Lorenz, 2007) and web transportation systems (Chen, Yin, Xiong, & Quan, 2009). Here, tension and speed usually have to be controlled independently, but the basic ideas can also be adopted to control rotational speed and torque on a drive train test bed.

As already mentioned, the second important requirement in addition to decoupling rotational speed and torque is the damping of resonance oscillations in the multi-mass mechanical system with potentially low internal damping. These torsional vibrations can be excited by a change in load torque, by gear play or by torque harmonics from the electric drives (Plotkin, Stiebler, & Hofmeyer, 2005) and from the mechanical test set-up including the unit under test (Welbourn, 1979). There are many publications dealing with oscillation damping in two- or multi-mass systems available as e.g. Wipfler, Bauer, Dourdoumas, and Rossegger (2016), Szabat and Orlowska-Kowalska (2007), Thomsen and Fuchs (2009), Schmidt and Lorenz (1992), Yuki, Murakami, and Ohnishi (1993), Jinbang, Wenyu, Anwen, and Yu (2013). However, most of these applications require speed control and vibration damping to be accomplished using just one electric drive. This restriction always leads to a compromise because an improved speed control performance typically comes with worse oscillation damping properties (Szabat & Orlowska-Kowalska, 2007). However, when a power train test bed has to be controlled, at least two electric drives are available; this can be utilised to improve oscillation damping without negatively affecting the speed control performance.

Although this work focusses on test beds for differential gears, the basic ideas can also be applied to control test beds for other power train components. The paper is structured as follows: in Section 2 a description of a typical test bed is given and the control objectives are specified. In Section 3 a simplified mathematical model describing the relevant dynamics of the test bed is presented. In Section 4 a decoupling network based on feedback-linearisation including active oscillation damping is developed to be able to independently control rotational speed and torque. Additional feedback controllers for rotational speeds and torque and implementation issues are discussed in Section 5. Various simulation studies in Section 6 and experimental results presented in Section 7 show that the proposed new control concept based on input–output decoupling and active oscillation damping results in improved control performance. Finally, in Section 8 a short summary and conclusions will be given.

## 2. System configuration and problem statement

Fig. 1 shows a typical test bed configuration for the testing of differential gears. This test bed can be used to test a wide variety of differential gears, which can be axle or centre differentials, passive or electronically controlled and possibly slip-limiting. Typically, three electric drives are needed to perform the required tests. Machine M1 provides the testing torque to emulate combustion engine and gearbox, while machines M2 and M3 are used to generate the mechanical loads. The test set-up discussed in this paper also includes three gearboxes. These are used to increase the torque by reducing the rotational speed to reach the required testing conditions (total load torque up to 60 kNm). Gearboxes and electric drives as well as gearboxes and differential gear are coupled via double cardan shafts. Each of the three induction machines is equipped with a torque flange to measure the shaft torque and with an incremental encoder to measure the rotational speed. Fortunately the cardan shafts, the gearboxes and the electric drives at the two outputs of the differential gear are typically identical while the input side is different. This simplifies system modelling and control.

The real-time control system shown in Fig. 1 is used to control the test bed. Depending on the type of test that should be performed different control modes are available. These range from complex strategies based on road load simulations including models for vehicle dynamics (Bauer, 2011) to just follow some given reference torques and rotational speeds. This special control problem will be further investigated in this work because efficient speed and torque control is fundamental also for other control modes. A higher-level system typically provides the reference signals for the differential gear's total output torque $T_{sum}$ and the rotational speeds of the output drives M2 and M3. These references can be completely available at the beginning of the test run, but they can also be generated at runtime. The real-time control system is used to perform feedback speed and torque control to be able to track the references with high dynamic performance and without steady-state error and to control the inverter-fed induction machines. In this paper however it is assumed that controllers for the electric drives based on field-oriented control (FOC) providing four-quadrant operation are already available and the focus will be placed on speed and torque control.

As mentioned before, the coupling of rotational speed and torque should be eliminated by using multiple-input multiple-

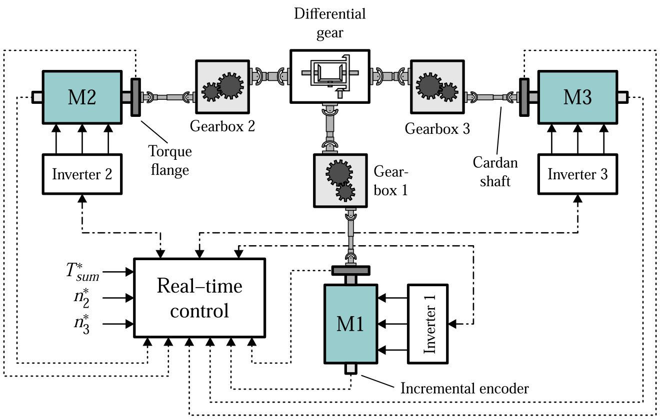

**Fig. 1.** Test bed configuration.