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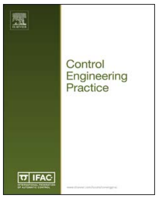

Virtual shaft: Synchronized motion control for real time testing of automotive powertrains

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ABSTRACT

The complexity of automobile powertrains continues to rise, leading to increased development time and effort. Synchronous testing with spatially distributed test benches allows improvements by front-loading of the validation phase. Nevertheless, virtualization of the mechanical interaction of shaft connections is required. A virtual shaft algorithm (VSA) is investigated for synchronized motion control in separate test benches. The behavior of a rigid mechanical shaft is analyzed and modeled. The mechanical shaft is substituted by two electrical motors and a superimposed VSA controller. This virtual shaft is established between two test benches for a combustion engine and a mechanical transmission. Control algorithms for synchronized motion control, known from web machines and force feedback, are analyzed. A controller layout with separate torque and speed controllers is implemented and analyzed through transfer function mathematics. The controllers are parametrized analytically for different gears. The effect of communication delay on the VSA is analyzed by simulation. The open clutch situation is handled by deactivation of the torque feedback. Validation on real test benches shows small deviations for torque and speed. Further work will focus on the necessity of system knowledge for controller layout and on the transient behavior during shifting.

1. Introduction

The rising number and complexity of components in modern powertrains has led to significant efforts in development and testing. Virtualization allows one to shift tasks to earlier project phases (front-loading) by utilizing specialized test benches instead of prototype vehicles (road to rig) (Dodds & Plummer, 2001; List & Schoeggl; Pelkmans & Debal, 2006; Sciuto & Hellmund, 2001), thereby enabling the test procedure on the road to be replaced by a test bench with simulated vehicle and road components. During development, each element of the powertrain is analyzed separately by considering component-specific requirements. Combustion engine test benches offer excellent possibilities for emission and efficiency analysis. Transmission test benches are focused on durability tests and noise, vibration and harshness analysis. Powerful electric motors can be used to simulate the high torques at the vehicle's wheels.

In Andert & Savelsberg (2015) and Andert, Huth, Savelsberg & Politsch (2015), the road-to-rig idea is explored and extended by connecting multiple test objects to a cyber-physical system with a virtualized mechanical shaft connection. The aim of this approach is to couple component test facilities to a virtual powertrain test bench with a superordinated control logic that emulates a mechanical shaft connection (Fig. 1).

Each of the testing facilities consists of a controlled electric load machine at the open end of the test object. The superimposed controller synchronizes speed and torque in a way that corresponds to a rigid shaft connection with low inertia and high stiffness.

The synchronization of multi-motor systems to substitute mechanical shafts is implemented in most industrial web machines and the theoretical background is well known in control theory (Anderson, Meyer, Valenzuela, & Lorenz; Liu, Li, & Zhang, 2012; Lorenz & Schmidt; Payette, 1998, 1999; Sun, 2003; Tomizuka, Hu, Chiu, & Kamano, 1992). A good survey for the past 20 years is given by Pérez-Pinal, Nuñez, Álvarez, and Cervantes. However, in all investigated approaches and realizations derived from industrial

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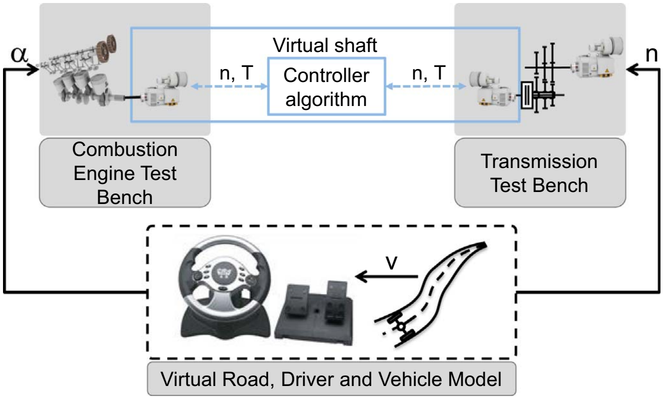

Fig. 1. New testing approach employing synchronized motion control emulating a mechanical shaft (Andert & Savelsberg, 2015).

application, the speed and partially the angular position are controlled. For a substitution of the mechanical shaft in automotive powertrain testing, the torque must be synchronized as well; this is not covered by state-of-the-art approaches.

A more similar technical realization is the steer-by-wire approach with force feedback. In conventional steering systems, the steering wheel is mechanically connected to the front wheels. In the steer-by-wire approach, one substitutes this connection with a steering motor and a feedback motor, both of which are electric motors. In the past few decades steer by wire has attracted particular attention (Bertoluzzo, Buja, & Menis, 2007; Kenned & Patil; Wang et al., 2014). In most approaches, the measured and processed steering wheel angle defines the set point of the front wheels and the measured wheel torque is superimposed on the steering wheel torque applied by the driver to get realistic steering feedback.

This control structure represents a kind of a coupled system and seems to be very similar to the virtual shaft setup proposed in this paper. However, the requirements and the problems differ here. The master and slave topology of steer by wire has two operating directions. The steering wheel position is used as an externally defined set point, and the reaction force is fed back with a low gain to the driver. Because power-assisted steering is required, feedback torque and mechanical power at the feedback motor are significantly lower in comparison to the wheel actuator. Owing to the constrained torque feedback and the stabilizing driver behavior, instability and oscillations can be avoided and the system can be considered as two separate single-input and single-output systems (Amberkar, Bolourchi, Demerly, & Millsap).

In contrast, coupling in the virtual shaft algorithm (VSA) is identical in both operation directions with the same priority. The resulting system interactions and the effects on controller layout will be discussed in this paper.

2. Theory

2.1. System model

The first step in substituting a real mechanical shaft by a virtual shaft connection is the understanding and the mathematical description of its behavior. A simple model for a physical shaft, in which torsion, stiffness, and distortion are neglected, is an inertia with two applied torques at each end of the shaft. A measurement point divides the moment of inertia into two subinertia (Fig. 2). Under these considerations, the physical description of the measured torque can be written in two ways:

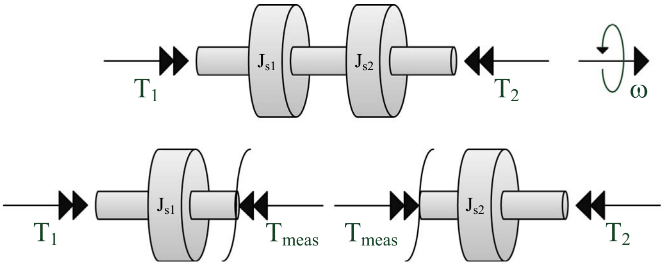

Fig. 2. Ideal mechanical shaft with torque measurement.

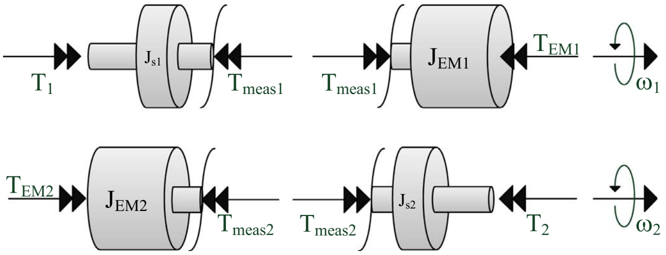

Fig. 3. Divided virtual shaft with ideal internal torque sources and inertias.

$$T_{meas} = T_1 - J_{s1} \cdot \dot{\omega},\ T_{meas} = J_{s2} \cdot \dot{\omega} + T_2. \tag{1}$$

Elimination of $\dot{\omega}$ in Eq. (1) and conversion in terms of T_{meas} leads to

$$T_{meas} = \frac{T_1 \cdot J_{s2} + T_2 \cdot J_{s1}}{J_{s1} + J_{s2}}. \tag{2}$$

The rotational speed ω can be described depending on two out of three shaft torques $T_{1/2}$ and T_{meas}, accordingly:

$$\omega = \int_{-\infty}^{t} \frac{T_1 - T_{meas}}{J_{s1}} dt = \int_{-\infty}^{t} \frac{T_{meas} - T_2}{J_{s2}} dt = \int_{-\infty}^{t} \frac{T_1 - T_2}{J_{s1} + J_{s2}} dt. \tag{3}$$

Eqs. (1)–(3) will be used to describe the reduced physical behavior of a shaft with reference to a measurement point.

A separation of the ideal shaft into two systems without a mechanical connection is then conducted (Fig. 3). The respective open end is connected to an electric motor that simulates the mechanical shaft connection. The inertias $J_{s1/2}$ describe the inertia of the divided ideal shaft as shown previously in Fig. 2. Both electric motors are represented by torque sources $T_{1/2}$. The additional inertia of the electric machine cannot be neglected and is represented by $J_{EM1/2}$.

The target of the VSA is to control the divided systems in a way that corresponds to the reference layout (see Fig. 2). Eq. (4) shall be fulfilled at any time. If this requirement is fulfilled, the separate systems interact exactly like the reference system and any influence of the inertia $J_{EM1,2}$ is compensated implicitly.

$$T_{meas1} \overset{!}{=} T_{meas2} \overset{!}{=} T_{meas} \omega_1 \overset{!}{=} \omega_2 \overset{!}{=} \omega \tag{4}$$

According to the proposed structure and with Eqs. (1)–(3), the torque and speed of both systems is described by

$$T_{meas1} = \frac{T_1 \cdot J_{EM1} + T_{EM1} \cdot J_{s1}}{J_{EM1} + J_{s1}},\ T_{meas2} = \frac{T_{EM2} \cdot J_{s2} + T_2 \cdot J_{EM2}}{J_{EM2} + J_{s2}},$$
$$\omega_1 = \int_{-\infty}^{t} \frac{T_1 - T_{meas1}}{J_{s1}} dt,\ \omega_2 = \int_{-\infty}^{t} \frac{T_{meas2} - T_2}{J_{s2}} dt, \tag{5}$$

with