

Adaptive Linear Quadratic Control for High Dynamical and Comfortable Behavior of a Heavy Truck

Lena Webersinke, Lutz Augenstein and Uwe Kiencke
Institute of Industrial Information Technology, Universität Karlsruhe (TH), Germany

Mario Hertweck
Daimler AG, Germany

Copyright © 2008 SAE International

ABSTRACT

During the last few years numerous innovations in advanced driveline control have improved the performance of commercial vehicles. In this context a major goal of driveline control is the enhancement of dynamical behavior and driving comfort. However, fast engine torque changes during Tipin and Tipout operations improve the dynamical behavior but induce unintentional driveline jerking at the same time. Due to this fact that comfort is contradictory to dynamic, a control strategy is necessary, which can handle with both targets at the same time. Based on a simple model of the driveline two Linear Quadratic (LQ) controllers are developed: A comfort controller, which damps the driveline oscillations, and a dynamic controller, which guarantees a high dynamical performance. However, as both controllers have different targets it is not possible to activate both at the same time. Therefore, a fusion of both manipulated variables dependant on the driving situation and the drive input is integrated.

The second main focus of this article is on the problem of dealing with time varying parameters. Adapting the LQ-controllers to these changes by an on-line identification method based on recursive least-squares estimation is indispensable for a good performance.

Both resulting algorithms – the offline and the online advanced LQ-controllers – are validated in simulation and show a very good improvement of the dynamical

behavior as well as the driving comfort at the same time.

INTRODUCTION

Driving comfort is getting increasingly important in heavy trucks. Due to the construction of the driving cab in heavy trucks, driveline resonances have a larger impact on the driver as in passenger cars. Therefore, the reduction of driveline oscillations would improve the comfort for the driver and reduce the wear of the driveline at the same time. However, improved comfort results in a decrease of the vehicle dynamics. The dynamical behavior of a vehicle can be described by the speed of acceleration. As fast changes in the velocity lead to uncomfortable driveline oscillations, the comfort and the dynamic of a vehicle are in conflict with each other. Therefore, finding the best compromise between both aspects is indispensable for a good driving performance.

In the following the driving situation of a Tipin and a Tipout will be considered, due to the aim to optimize acceleration procedures.

The common solution of the described conflict is to limit the grade of the engine torque during a Tipin/out to avoid high oscillations on the driveline. Figure 1 shows the results of this approach tested in a test truck. Therein, the solid line represents the engine torque and the dashed line represents the difference between the rotational speed of the engine and wheels. The influence of the fast changes in the engine torque on the driveline, which is dependent on

the step height and the gradient, can be seen in the oscillations. However, although the impulse of the oscillations – the step in the engine torque – is reduced, the comfort described by the driveline oscillations is very bad. In addition the limited engine torque leads to a reduced dynamical behavior. This approach can not be considered as a solution to our problem due to an inadequate comfort as well as limited dynamics.

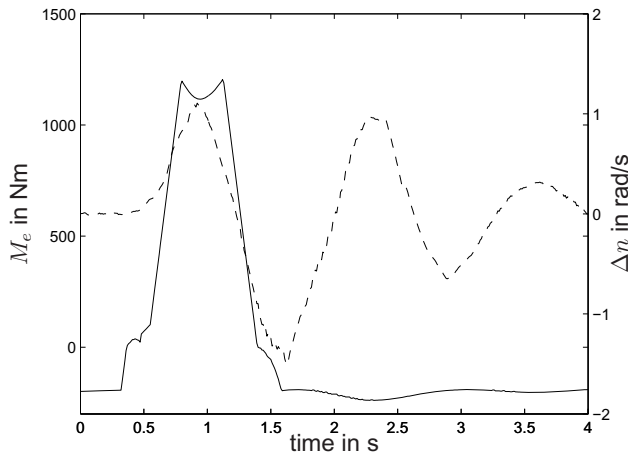


Figure 1: Engine torque changes and its impact on the driveline for the common solution;—engine torque,— —difference between the rotational speed of the engine and wheels

Therefore, in a further development (see [1]) an advanced PD-Controller combined with no limitations on the engine torque was tested. Fewer driveline oscillations lead to an increased comfort and the unlimited engine torque to an acceptable dynamic.

However, the compromise of this second approach is not optimal. As the controller supports only the comfort of the truck, the dynamical behavior is inadequate. However, by changing the parametrization of the controller it is not possible to obtain higher dynamics.

Therefore, in this paper a new approach is considered which supports the comfort as well as the dynamic. The basis of this concept are two different model based controllers. The underlying simplified model of the driveline is introduced first. Afterwards the advanced LQ-controller structure is described and validated. The compromise between comfort and dynamic is found by a fuzzy fusion with respect to the driving situation and the drive input. The background of this fusion is the idea to support the dynamic in all driving situations until it is necessary to increase the comfort. These aspects are considered in a new section. In addition an adaptation algorithm is included to make it possible for the controller to react to a chang-

ing vehicle mass, different truck types and unmodeled dynamics. Finally a conclusion summarizes this work.

DRIVELINE MODEL

First of all, a driveline model, which describes the behavior adequately, is necessary. We distinguish between two different models: The controller algorithm is based on a model, which should be as simple as possible while describing the dynamics very well. Due to the complex behavior of the driveline, a more detailed model is used for a significant validation.

In the following the simple model used in the controller algorithm will be introduced and contrasted to the construction of the driveline.

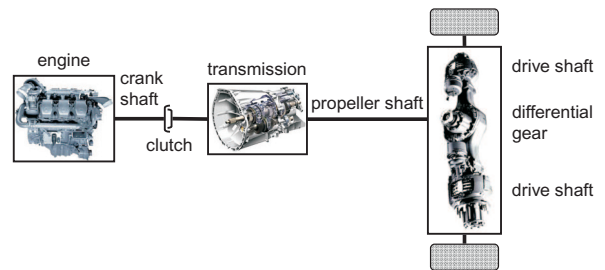


Figure 2: The construction of the power train

The construction of the power train is illustrated in figure 2. The engine torque is transmitted successive to the crank shaft, the clutch, the transmission and the propeller shaft. At the differential gear, the transformed engine torque is passed to the drive shafts. Finally the wheels connect the driveline to the street.

For simplification only one shaft is considered as flexible. As the predominant oscillations occur in the drive shaft (see also [2] and [3]), the flexibility of the other shafts is neglected. The air drag as well as most of the road repercussion are not considered to keep the model linear. Hence, the driveline can be simplified described by a two mass spring model, which can be seen in figure 3. Therein, the moments of inertia from

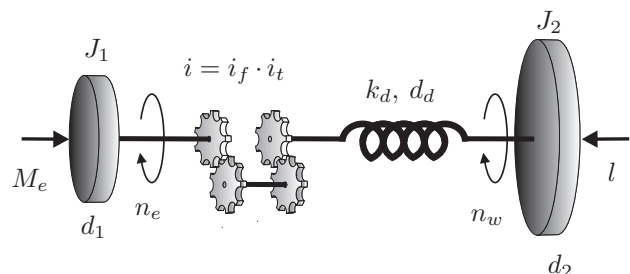


Figure 3: The drive shaft model

the engine to the differential gear are summarized to

J_1 . The drive shaft is modeled as a spring damper element with the damping d_d and the stiffness k_d . The second moment of inertia J_2 comprises the remaining driveline.

This model is represented in a state-space formulation as in equation (1) with three states: the torsion of the drive shaft $\Delta\alpha$, the rotational speed of the engine n_e and the rotational speed of the wheels n_w . The manipulated variable u is the engine torque M_e .

$$\begin{aligned}\dot{x}_1 &= \frac{1}{i}x_2 - x_3 \\ \dot{x}_2 &= \frac{1}{J_1}u - \frac{1}{J_1}\frac{k_d}{i}x_1 - \frac{1}{J_1}(d_1 + \frac{d_d}{i^2})x_2 + \frac{1}{J_1}\frac{d_d}{i}x_3 \\ \dot{x}_3 &= \frac{1}{J_2}k_dx_1 + \frac{1}{J_2}\frac{d_d}{i} - \frac{1}{J_2}(d_d + d_2)x_3\end{aligned}\quad (1)$$

The resulting model was identified by quadratic programming using measured data of the rotational speeds. A validation of the identification results confirms the good analogy of the model and the reality in the dynamical behavior of the driveline. However, the results in the higher gears are not as good as for the lower ones but still acceptable. Due to the simplicity and the adequate coverage of the dynamical behavior, this so called "drive-shaft model" is used for the controller development in the next section.

However, for a significant validation a more detailed model is necessary. Therefore, a model with less negligence is used. Further on, this model will be called "simulation model".

LQ CONTROL

As control method the Linear Quadratic controller (LQ) was chosen. The advantages of this technique are the robust behavior as well as the easy way to formulate a control target in opposite to the pole placement method. The robust behavior is necessary due to the simple driveline model. Due to the fact that the LQ-controller is a state-feedback controller, all states must be known. However, the torsion of the drive shaft cannot be measured in our system. Therefore, a Kalman filter is used to calculate the current driveline torsion.

The aim of the controller is on the one hand to maximize the comfort and on the other hand to increase the dynamic. However, having such two contrasted control targets it is not possible for a controller to reach both in a suitable manner. Therefore, for each control target one controller is designed. In the following the LQ-controller for high comfort is called "comfort controller" and the one for increased dynamic "dy-

namic controller". Each of these two controllers calculates a manipulated variable independently from the other. However, finding the best combination of both controllers, which is equal to find the best compromise for the control targets, is not trivial. By merging the manipulated variables in a suitable manner dependant on the drive input and the driving situation the activation of both controllers is regulated. This algorithm is introduced in the following section.

In a first step the concept for the comfort controller is introduced. Increasing the comfort is set equal to minimize the oscillations in the driveline. These oscillations are described by the difference of the rotational speed of engine and wheels Δn as described in the introduction. Due to the possibility of measuring this control variable directly, an calculation error will not occur. The goal of the comfort controller is to control the difference of rotational speeds to zero.

The common used LQ-controller with a single control signal u is described in [4]. The cost function

$$J = \lim_{T \rightarrow \infty} \int_0^T (\underline{m}^T \underline{x})^2 + \eta u^2, \quad (2)$$

where $\underline{m}^T \underline{x}$ represents the weighted model states and η is a controller design parameter, is to be minimized to find the controller output. With the following weighting vector

$$\underline{m}_{\Delta n}^T = \begin{pmatrix} 0 & \frac{1}{i} & -1 \end{pmatrix} \quad (3)$$

(4)

it is possible to create a cost function, which minimizes the difference of the rotational speeds. The resulting manipulated variable for the comfort controller is calculated to

$$u_C = -\underline{K}_c \underline{x} \quad (5)$$

with the controller matrix

$$\underline{K}_c = \eta^{-1} \underline{b}^T \underline{P}, \quad (6)$$

therein the matrix $\underline{P}$ is the solution of the Riccati equation.

The dynamic controller is designed very similar. A suitable control variable should describe the dynamic the driver requires. Due to the fact that by changing the adjustment of the acceleration pedal the driver wants to influence the vehicle speed, the rotational speed of the wheels n_w is a suitable dynamic control variable. Therefore, a reference speed is calculated to represent the required dynamic. The value of this reference speed n_{ref} is dependant on the driving situation as can be seen in equation (7).

$$n_{ref} = \begin{cases} n_{ref,ideal} & \text{if Tipin} \\ 0 & \text{if Tipout} \end{cases} \quad (7)$$