

Signal Generator for Prediction of Transient Control Signals of an Automotive Transmission Control Unit Depending on Scalar Calibration Parameters

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ABSTRACT

In this investigation an innovative signal generator will be introduced, which enables the generation of transient control signals for the gearshift process. The signals are generated merely depending on scalar transmission control unit (TCU) calibration parameters. The signal generator replaces the comprehensive TCU software within the simulation environment. Thus no extensive residual bus simulation is required.

Multiple experimental models represent the core part of the signal generator. To predict the system behavior of the underlying system, the models are trained using measured data from a powertrain with automatic transmission mounted on a test rig.

The results demonstrate that the introduced signal generator is suitable to predict transient control signals for the gearshift operation accurately. In combination with an additional powertrain model it is possible to simulate the gearshift process and subsequently to evaluate the gearshift comfort. The signal generator allows a rapid implementation of a simulation environment for TCU calibration with less modeling effort in comparison with the implementation of the original TCU software. Due to a flexible approach, the signal generator offers to predict signals with any course. Hence, it also allows to predict gearshift-comfort relevant signals directly without using a powertrain model. In conclusion the introduced signal generator emphasizes an universal tool with high potential for model based calibration.

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INTRODUCTION

Due to rising demands on driving comfort, the complexity of vehicle powertrain components is increasing continuously. Especially the number of functions and parameters of the transmission control unit (TCU) rises strongly. To achieve a high customer acceptance, these TCU parameters must be calibrated with respect to high gearshift comfort. Because of growing variant diversity and shortened product development time, the calibration task constitutes a challenge but also a key aspect in further vehicle development. In future, tools and methods are required for an efficient adjustment of calibration parameters. For combustion engines, model based calibration methods are established and represent a promising approach to calibrate the engine control unit (ECU) parameters effectively [1]. Model based methods for TCU parameter calibration are in development and are not common in practice so far. For computer-aided calibration a powertrain model may be used to simulate the behavior of the system. Furthermore the functionality of the TCU software is needed to calculate certain signals for engine and clutch control during the gearshift operation. The transient progresses of these control signals depend on the TCU calibration parameters and influence the gearshift process and the gearshift comfort respectively. The TCU software is linked with the powertrain model to accomplish a complete software-in-the-loop (SIL) simulation environment. This

software requires certain state quantities of the powertrain, which have to be simulated explicitly and accurately by the model. Furthermore a residual bus simulation for all input signals of the TCU software has to be implemented, which normally are not provided by a simplified powertrain model. The implementation of a TCU model, which provides the original TCU software functionality, is very extensive and time-consuming. For the modeling task, detailed knowledge of the TCU software is required. This knowledge may be obtained from the manufacturer. Alternatively, using information from general literature merely allows creating an universal model of TCU software, which may not be compared with a certain manufacturer's TCU functionality. Moreover a large number of measured data is required to adjust the parameters of a TCU model [24].

In further progress of this work a signal generator will be introduced, which offers the same functionality of the TCU software regarding the generation of transient control signals during a gearshift process. The signal generator enables a time efficient implementation of a simulation environment and represents a promising tool for model based TCU calibration.

GEARSHIFT PROCESS OF AN AUTOMATIC TRANSMISSION

During vehicle acceleration the engine generates the torque T_E to drive the downstream components. This torque is converted by the torque converter and the planetary gearbox. The planetary gearbox contains multiple clutches or brakes, which lock the gear sets to each other or to the gearbox housing. Depending on the clutches states various gear ratios can be realized. Before the command for a gearshift is triggered, the torque is completely transmitted by clutch $C1$ and the gear ratio of the current gear is i_1 . During the gearshift operation, in general two clutches are acting at the same time. Within the process one clutch is disengaging ($C1$) and the other clutch ($C2$) is engaging simultaneously, whereas the torque is transmitted via both actuating clutches. After the second clutch is fully engaged the complete torque is transmitted via clutch $C2$ and the gear ratio of the following gear is i_2 .

Furthermore the powertrain contains different control units, which set control signals on certain powertrain components depending on the driver demands and the current system states. During a gearshift process the actuated clutches are controlled by the TCU. The transmission control unit calculates a current for each clutch. This current actuates directly an electrohydraulic valve, which sets a pressure for clutch actuation. Additionally the TCU also requests a desired engine torque to increase the gearshift comfort or the gearshift sportiness. A schematic overview of the characteristic signals which exemplary describe the traction upshift process is shown in [Figure 1](#). Both the target pressures $p_{C1,T}$ and $p_{C2,T}$ of the operating clutches and the engine torque T_E influence the turbine speed n_T and the vehicle acceleration a_{veh} directly. The course of these signals is determined by the TCU calibration parameters $P(1), \dots, P(L)$, which may be calibrated according to individual requirements.

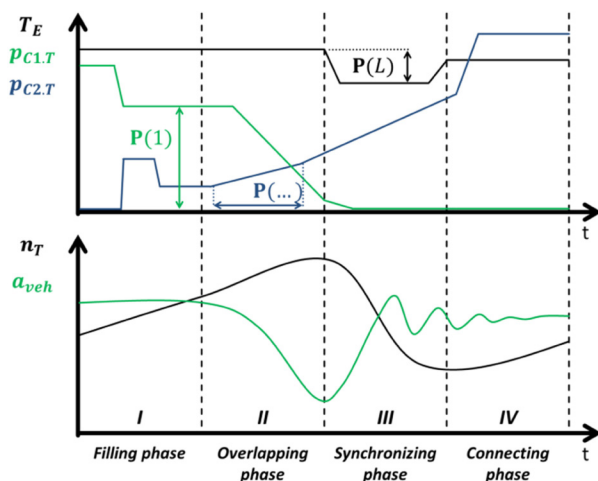


Figure 1. Phases and relevant signals of the traction upshift gearshift operation

The whole gearshift process can be subdivided into four characteristic phases. The filling phase begins after the gearshift command is initialized. To provide a defined initial state for the

engaging clutch, the target pressure increases rapidly to prefill the electrohydraulic unit with fluid. Concurrently the target pressure of the disengaging clutch $C1$ drops to a pressure level, where the clutch is still in stick state. During the overlapping phase, the target pressure of the engaging clutch begins to increase continuously while the target pressure of the disengaging clutch decreases simultaneously. Thus, the transmitted torque is transferred from clutch $C1$ to clutch $C2$. In the synchronizing phase, after the transmitted torque is completely transferred to clutch $C2$, the disengaging clutch passes into the slip state and the turbine speed begins to synchronize to the target speed of the following gear. During the speed synchronization the engine reduces its torque to support the synchronization process. After the turbine reaches the target speed the engaging clutch passes into the stick state. In the final connecting phase the target pressure of clutch $C2$ increases abruptly to ensure that this clutch remains in the stick state.

Depending on the operating point and the underlying control strategy, the TCU also calculates a target pressure signal for the actuation of the torque converter clutch. The torque converter clutch allows a desired slip between pump and turbine of the torque converter and increases primary the fuel consumption efficiency.

SIGNAL PREPROCESSING

The signal preprocessing is required to prepare a dataset for parameter estimation of the signal generator. In the first step, single upshift events are extracted from the entire measured signal, which contains differently calibrated gearshifts. For this purpose, the start point of each upshift is identified via the clutch control state ($STAT$), which is used to define a reference point RP for each gearshift signal. The reference point allows extracting the signals in order that each signal begins from the same sampling point. Both all extracted signals and all predicted signals using the signal generator are related to this particular reference point. Thus, each value of a sampling point characterizes a certain discrete property of the extracted signal during the gearshift operation.

From top to bottom, the first and the second diagram in [Figure 2](#) show 15 exemplary target pressure signals of the engaging clutch within the same operating point (constant turbine speed and load at gearshift request) for different calibrated traction upshifts. These signals were extracted and subsequently superposed. Additionally a second signal is plotted, which describes the current discrete clutch control state of the disengaging clutch $STAT$ during the gearshift operation. Each extracted signal is put into a data set and has the same time length or the same number of sampling points respectively. In this example the total number of sampling points N_{total} of each extracted signal is 701. This quantity is defined as $N_{total} = N_a + N_b$ and consists a range of sampling points before (N_a) and after (N_b) the reference point RP (see [Figure 2](#)). Both ranges may be predefined and are valid for each extracted signal, whereas N_b should be large to capture also prolonged gearshifts.

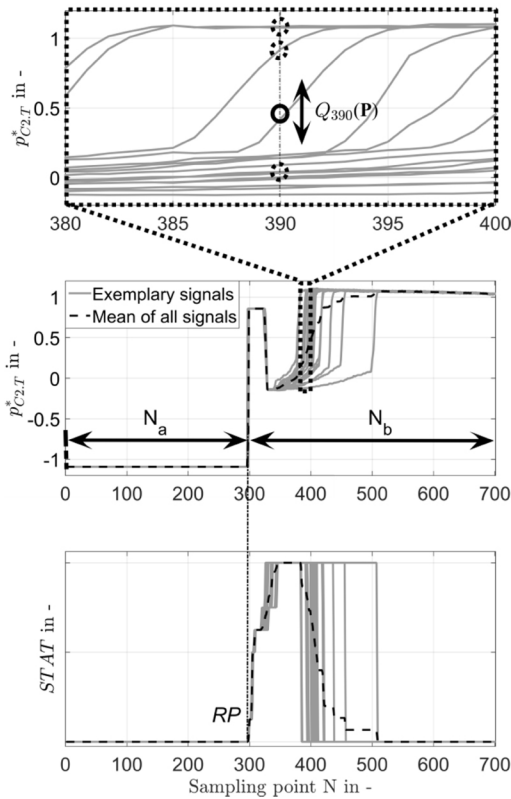


Figure 2. Scaled target pressure and control state signals of 15 different calibrated gearshifts

SIGNAL GENERATOR

The task of the signal generator is to predict transient TCU signals for gearshift control depending on scalar TCU calibration parameters. The relevant control signals, which are directly influenced by the TCU calibration parameters, are the desired engine torque and the control currents for both active clutches inside the planetary gearbox during the gearshift process. To simplify the powertrain model, the effective engine Torque T_E and the target pressures $p_{C1,T}$ and $p_{C2,T}$ are used for prediction using the signal generator. These signals are provided directly by the engine control unit (ECU) and the TCU respectively.

Owing to the fact that all preprocessed signals are referring to the same reference point RP , the value of each individual sampling point depends clearly on the corresponding calibration parameter set $\mathbf{P}$. This correlation between the calibration parameters and the value of each sampling point constitutes the key element of the introduced signal generator.

For each sampling point N , the signal generator contains an individual function $f_{EM,N}(\mathbf{P})$, which exclusively predicts the assigned signal value Q_N on the sampling point N depending on the TCU calibration parameter set $\mathbf{P}$:

$$Q_N = f_{EM,N}(\mathbf{P}). \quad (1)$$

In this work, the nonlinear functions $f_{EM,N}(\mathbf{P})$ are represented by experimental models (EMs), which will be explained in the further course.

Once all values $\mathbf{Q} = Q_1, \dots, Q_{N_{\text{total}}}$ were predicted, they are processed by the function $f_{SG}(\mathbf{Q})$. The function reconstructs the desired signal passing through the signal nodes $\mathbf{Q}$. Additionally, this function also resamples the outcome signal $S(t)$ by linear interpolation if needed and assigns all sampling points a corresponding timestamp. In Figure 2, an exemplary node $Q_{360}(\mathbf{P})$ on sampling point $N=390$ is presented, which may adopt different values along the ordinate depending on $\mathbf{P}$.

The output of the processing function is the signal $S(t)$:

$$S(t) = f_{SG}(\mathbf{Q}). \quad (2)$$

Before the measured signals were used to train the behavior of the experimental models within the signal generator, they are scaled by the following equation [22]:

$$P^*(W) = \frac{P(W) - \bar{P}(W)}{\sigma_{P(W)}}, \quad (3)$$

$$Q_N^* = \frac{Q_N - \bar{Q}_N}{\sigma_{Q_N}}, \quad (4)$$

with the means $\bar{P}(W) = \frac{\sum_{q=1}^R P_q(W)}{R}$ and $\bar{Q}_N = \frac{\sum_{q=1}^R Q_{q,N}}{R}$ and the standard deviations $\sigma_{P(W)} = \sqrt{\frac{\sum_{q=1}^R |P_q(W) - \bar{P}(W)|^2}{R-1}}$ and $\sigma_{Q_N} = \sqrt{\frac{\sum_{q=1}^R |Q_{q,N} - \bar{Q}_N|^2}{R-1}}$. The quantity W describes the index within the input parameter vector $\mathbf{P}$ and R is the number of measured data. Both quantities $\mathbf{P}$ and $\mathbf{Q}$ are referred to all measured signals. The scale of the data is required to eliminate the different orders of magnitude between each input and the output. Therefore all inputs have the same weight and thus the same impact on the process within the experimental model structure. The predicted output signal of the signal generator $S^*(t)$ is also scaled and has to be scaled back to the signal $S(t)$, which represents the input of the powertrain model (see Figure 3).

In general the introduced approach enables to predict a transient signal with any course. A schematic overview of parameter and signal processing of the signal generator is shown in Figure 3.

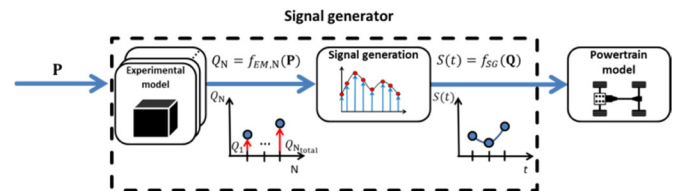


Figure 3. Schematic overview of the signal generator

ALLOCATION OF EXPERIMENTAL MODELS

As mentioned before each experimental model predicts the value of the signal on one certain sampling point. Therefore the maximum number of experimental models which may be used for signal prediction equals to the number of all sampling points within the

extracted signal. In this case the maximum quality of the predicted signal can be archived. On the other hand the number of experimental models increases the computational effort. The total computational runtime t_r increases linear to the number of experimental models n_{EM} :

$$t_r \in \mathcal{O}(n_{EM}). \quad (5)$$

Hence, in terms of computational effort it is more efficient to reject experimental models on sampling points, which has no significant impact on the course of the signal respectively. For a computational resource efficient allocation of experimental models a criteria-based, multi-stage approach is proposed. First, a number of experimental models has to be specified which depends on computational resources that are available for utilization. Subsequently the specified experimental models will then be allocated in four stages:

Within the first stage, overall two experimental models are allocated on the first and on the last sampling point of the preprocessed signal (see triangles in Figure 4).

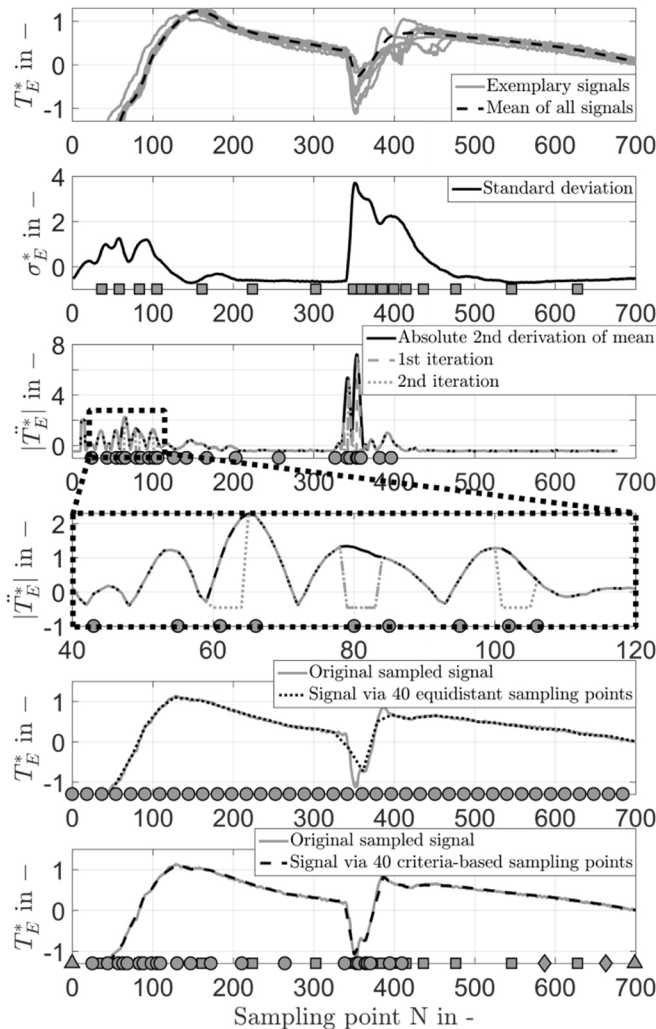


Figure 4. Criteria-based allocation of sampling points of the scaled engine torque signal

In the second stage the standard deviation on each sampling point N of all superposed signals $\sigma_{S,N}$ is used to allocate a predefined number of EMs ζ_σ . The consideration of the standard deviation is important in order to include the areas on the sampling point coordinate, where corresponding signal values have a wide valuation. The standard deviations on all sampling points are summed up to Σ_{σ_s} :

$$\Sigma_{\sigma_s} = \sum_{N=0}^{N=700} \sigma_{S,N}. \quad (6)$$

The sum of all standard deviations is divided by the predefined number of EMs ζ_σ :

$$\zeta_\sigma = \frac{\Sigma_{\sigma_s}}{\xi_\sigma + 1}, \quad (7)$$

where ζ_σ represents the imaginary boundary, which decides, where the EMs within the second phase have to be placed (see squares in Figure 4). This procedure is shown schematically in the code below:

Algorithm: 'Allocation procedure'

1. Set $c = 0$ (c is an auxiliary variable)
2. Set $N = 0$ (first sampling point)
3. Set $c = c + \sigma_{S,N}$
 - a. If c is larger than ζ_σ
 - b. Place EM at actual sampling point N
4. $c = c - \zeta_\sigma$
5. If $N == 700$
 - a. Brake 'Allocation procedure'
6. Set $N = N + 1$
7. Go to step 3.

To avoid an accumulation of EMs on particular locations, a minimum distance between neighboring EMs is introduced. If the distance is below the minimum distance, the mentioned EM is rejected on this particular sampling point N_{rej} . To ensure that all ζ_σ EMs are allocated by this procedure, the allocation process is performed iteratively. To avoid that EMs in further iterations are allocated at the same location the according values of $\sigma_{S,N}(N_{rej} - \frac{min. distance}{2}; N_{rej} + \frac{min. distance}{2})$ are set to zero. The rejected EMs will be placed by a further iteration, until there are exactly ζ_σ EMs allocated. A simplified schematic code of the iterative algorithm is shown below:

Algorithm: 'Minimum-distance-based reallocation'

1. 'Allocation procedure'
2. If neighboring EM's distance is smaller than the minimum predefined distance ($min. distance$)
 - a. Reject these specified EMs on $N_{rej} = N_{rej}(1), \dots, N_{rej}(end)$
 - b. Set $\sigma_{S,N}(N_{rej} - \frac{min. distance}{2}; N_{rej} + \frac{min. distance}{2}) = 0$ for each N_{rej} .