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CAE-supported design and testing of a signal conditioning subsystem for analog velocity measurement in position control applications

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Abstract

Analog measurement signals are usually biased by noise and offset, and may incorporate different nonlinear characteristics. Especially velocity measurements affected by offset and errors due to transducer gain deviation may severely influence the system performance in position control applications. A signal conditioning subsystem to compensate these types of linear and nonlinear disturbances is presented in this paper. Extensive CAE-support for control system design and implementation is applied for rapid feasibility studies and concept proving. A block-diagram oriented modular approach provides a proven signal conditioning library block reusable within the given class of applications.

1. Introduction

Many position control systems are set up with an analog velocity and a digital position measurement. These measurements may be accomplished by a tacho generator and an incremental encoder. Additionally, the drive and load side may be compliantly coupled, in which case the tacho generator is commonly placed at the drive side and the encoder at the load side for a precise positioning. This is the configuration of the electromechanical positioning system (EMPS) from figure 1 which is used as a test bench for the work described in this paper.

For ideal unbiased measurement signals the measurement equations are

$$\begin{aligned} tacho &= k_\Omega \cdot \Omega_d \\ incr &= k_\varphi \cdot \varphi_l \end{aligned} \tag{1}$$

where Ω_d is the drive-side angular velocity of the motor shaft, *tacho* the tacho generator output voltage, φ_l the load-side angular displacement of the ball screw, *incr* the digital data from the encoder counter register, and k_Ω and k_φ are the nominal transducer gains of the tacho generator and incremental encoder.

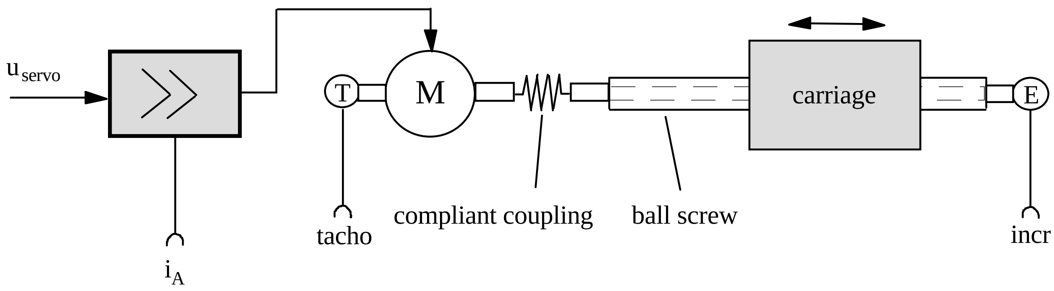

Fig. 1 *Sketch of electromechanical positioning system (EMPS)*

Mathematical modelling of the EMPS results in a fifth order state-space model with nonlinearities resulting from friction in the ball screw drive, tacho ripple, and encoder quantization. Servo amplifier and tacho noise as well as an offset on the tacho output voltage are added for a more realistic description of the system. Figure 2 shows the associated SIMULINK block diagram for nonlinear simulation.

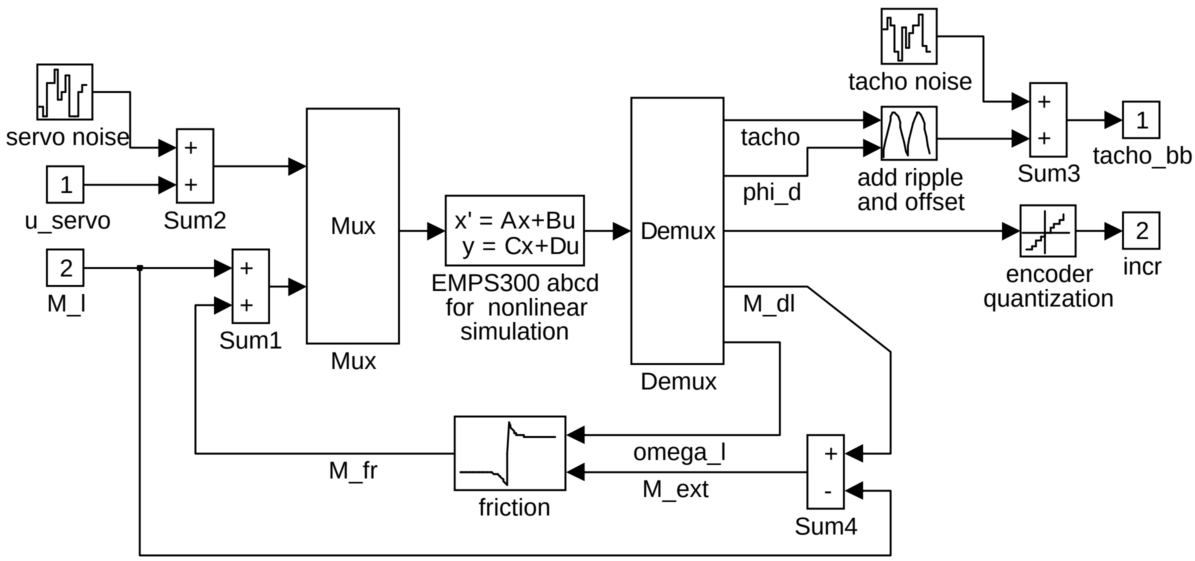

Fig. 2 *Block diagram of EMPS model*

Simulation is carried out for the controlled system, the EMPS in closed loop with a P-PI cascade controller consisting of an inner auxiliary PI-feedback for the tacho signal and an outer proportional feedback loop for the encoder output. Figure 3 shows the SIMULINK block diagram with the EMPS from Figure 2 as a subsystem, the controller, and additional blocks for reference profile and disturbance signal generation, I/O, and I/O scaling. A subsystem for tacho signal conditioning is also included in the block diagram. The importance of this subsystem for precise position control is the topic of this paper and will be shown in the following.

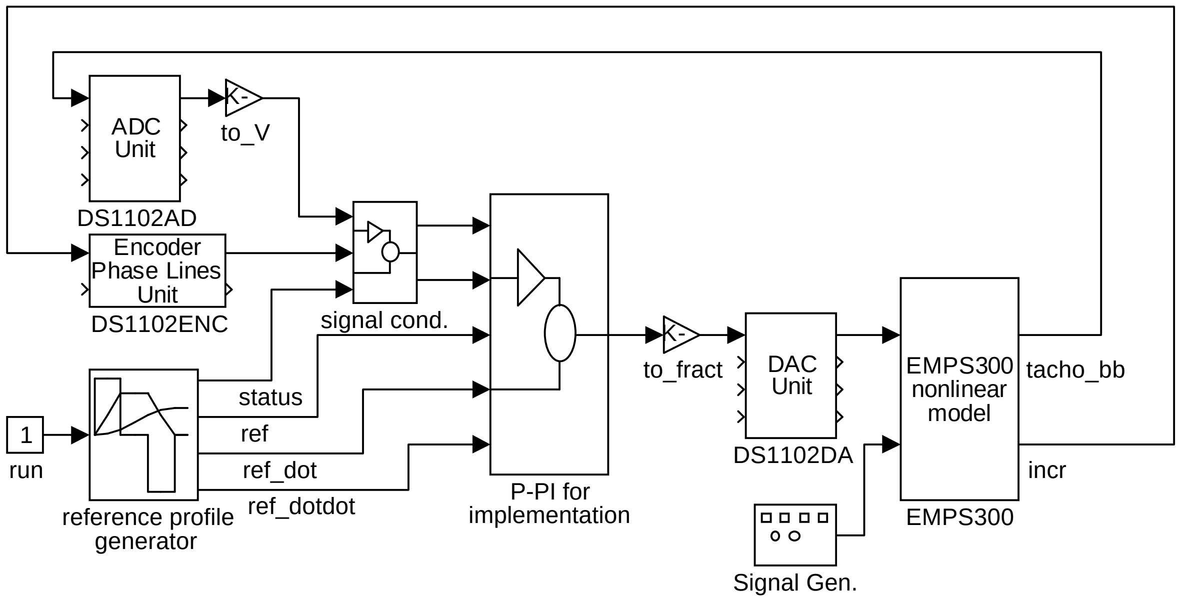

Fig.3 *Block diagram of EMPS with controller and tacho signal conditioning*

Intergrated development (CAE) tools have been extensively used for the subsystem design. Block-oriented modelling and simulation including the complete operational environment, as given in figure 3, provide all means for advanced feasibility studies. Rapid prototyping by automatic code generation was used for the final concept proving at the real EMPS. It took only minutes to proceed from an idea over modelling, design, and simulation to the experiment with the EMPS, i.e. through the complete system development cycle.

Before we present the results let’s explain the need of the tacho signal conditioning subsystem and how it works.

2. Conditioning of analog velocity measurement from tacho generator

Why is signal conditioning required for the tacho signal? The tacho output voltage used as a measure of the angular velocity is usually affected by noise, offset from the measurement electronics, and commutation ripple. In addition, due to manufacturing tolerances, the tacho generator transducer gain may deviate from the nominal value in the data sheet. While the control system can be designed robust against noise and ripple by simply limiting the control system bandwidth, thus reducing the effect of these disturbances on the positioning accuracy, offset and transducer gain deviation may lead to considerable position errors during reference profile tracking.

With a proportional position feedback, as it is considered here with the P-PI cascade control, the tacho offset will produce a permanent steady-state position error, since it has the same effect as an equivalent constant reference position command. A PI-PI-cascade controller could be a remedy for that, but it has the disadvantage of a reduced closed-loop system bandwidth and thus an increased decay time for transient errors.

Regardless of the selected control structure, the transducer gain deviation (which is up to 15% of the nominal tacho generator gain for the EMPS) may produce an unacceptable tracking error.

Thus, especially in high-speed and high-precision position control applications, measures are necessary to correct both, the tacho offset voltage and transducer gain deviation. Since manual adaptation of controller parameters to individual measurement setup and tacho generator properties which vary with operating conditions and age is not desirable, suitable pieces of software have been developed for automatic compensation of offset voltage and gain deviation. These can be added to the digital position control algorithm as ready-to-use blocks which only have to parametrized by the user for the specific mechanical system configuration. The corresponding algorithms are subsequently discussed for the EMPS.

2.1 Compensation of offset

Offset can be observed on the tacho output voltage in all phases of operation. However, the best situation to extract it from the biased tacho measurement signal *tacho_bb* is when reference velocity zero is commanded to the controller (*ref_dot = 0*) and the system has settled to stand still after some time. Since for zero velocity the tacho generator gain deviation becomes not effective to the measurement, we are only dealing with the offset in this case. Due to the noise added to the measurement the offset has to be determined as the mean value over a certain time horizon which can be accomplished by a simple first order low pass filter. By substracting the offset from the measurement we then get the offset-free signal *tacho_b* with the remaining gain deviation bias for non-zero velocity. Figure 4 shows the corresponding block diagram with the inputs *condition* and *tacho_bb* and the output *tacho_b* .

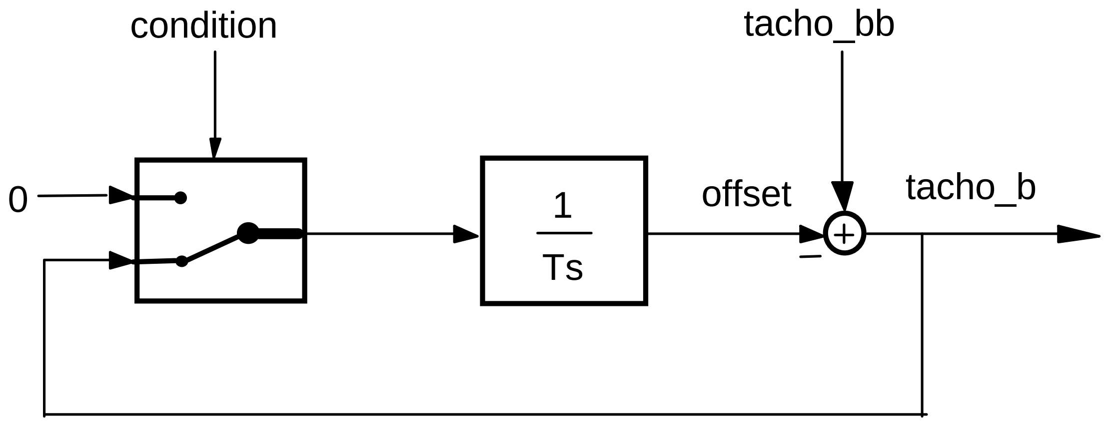

Fig. 4 *Block diagram of offset compensation*

If the input *condition* is true (*ref_dot* is zero and a certain waiting time has passed for the settling of *tacho_bb*), the mean value *offset* of the signal *tacho_bb* will be updated at the integrator output by feedback of the difference *tacho_bb* - *offset* to its input, building a first order low pass filter with time constant *T*. Otherwise the current value *offset* will be held by switching the integrator input to zero.

The above offset compensation has been implemented as a discrete time system. Discretization by backward-rectangular transformation of the integrator (replacing $s = (z-1)/(\Delta t\, z)$ in the continous first order lag transfer function and using the shift operation $x_{k-1} = z^{-1} x_k$ for a single sampling period Δt) yields the difference equations

$$\begin{aligned} offset_k &= offset_{k-1} + \frac{\Delta t}{\Delta t + T}\left(tacho\_bb_k - offset_{k-1}\right) \\ tacho\_b_k &= tacho\_bb_k - offset_k \\ offset_0 &= 0 \end{aligned} \quad . \qquad (2.1)$$

Together with the switching operation they have been programmed in C language as a SIMULINK S-Function block. To save execution time during simulation and real-time execution, the quotient $\Delta t / (\Delta t + T)$ is evaluated during the respective initialization phases. As mentioned above a certain waiting time had to be added to the code to allow the system to settle before the discrete integrator input is switched from zero to the difference $(tacho\_bb_k - offset_{k-1})$ and offset updating commences. This time has been implemented as a so-called relative time by the aid of a counter which is incremented each sampling step, starting at the time instant the condition *ref_dot = 0* becomes and remains true, and setting the input *condition* true when the count corresponding to the waiting time has been reached. The relative time is mandatory for real-time execution, which runs for an infinite time, to avoid accuracy problems due to the limited floating-point precision of the real-time hardware when adding small sampling periods to large absolute times.

Assuming that offset compensation is applied to the tacho signal, we now turn to the second bias due to transducer gain deviation.

2.2 Compensation of gain deviation

As already mentioned, the deviation of the transducer gain from its nominal value becomes effective to the tacho signal for non-zero velocity. The formula

$$r = \frac{\frac{d}{dt} incr}{tacho\_b} \cdot \frac{k_\Omega}{k_\varphi} \qquad (2.2)$$

is used to measure the gain error as the ratio of the derivative of the position measurement (encoder) signal *incr* and the offset-free tacho signal *tacho_b*, both scaled to a common level by the corresponding tranducer gains. Since the position measurement should be sufficiently precise for position control, the gain k_φ is considered to be exactly known. For the tacho signal produced by a deviating transducer gain the nominal gain k_Ω from the data sheet is used. Thus *r* is a number different to one, while for a correct transducer gain it would become equal to one.

If the measurement transducers are mounted in such a way that they are not rigidly coupled but separeted by compliancy, as it is the case for the EMPS, vibrational transients will appear in both the velocity and position signals. Since the formula is not valid for this, we have to exclude the corresponding time intervals from the above consideration. This is done by restricting the evaluation of (2.2) to the case of constant reference velocity (*ref_dot* = *const*) and again introducing an appropriate waiting time for the decay of transients.

Due to the noisy tacho signal and encoder quantization, *r* will also be affected by noise and quantization when calculated from the measurement signals. Thus its mean value $\bar{r}$ is of better use for the tacho gain correction. As for the offset compensation a first order lag filter is applied to provide the mean value. Now the product $\bar{r} \cdot tacho\_b$ reprensents the tacho signal with its overall tranducer gain corrected to the nominal gain. Figure 5 shows the complete block diagram for the tacho gain correction.

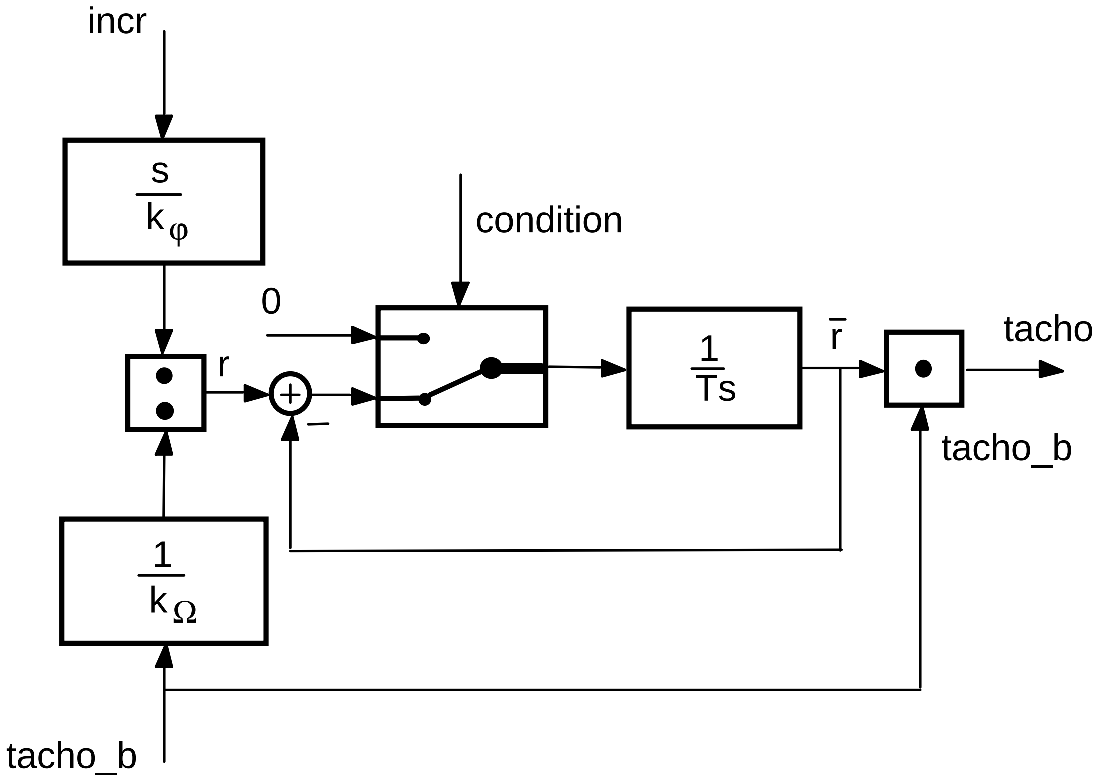

Fig. 5 *Block diagram of tacho gain correction*

If the input *condition* is true (the absolute value of *ref_dot* is constant and greater than a given threshold, and a certain waiting time has passed for decay of the transients), the mean value $\bar{r}$ of the filter input *r* will be updated for the gain correction. Otherwise the current value will be held by switching the integrator input to zero.

Discretization of the tacho gain correction by backward-rectangular transformation of the integrator for a sampling period Δt yields

$$\bar{r}_k = \bar{r}_{k-1} + \frac{\Delta t}{\Delta t + T}\left(r_k - \bar{r}_{k-1}\right)$$
$$tacho_k = \bar{r}_k \cdot tacho\_b_k \qquad (2.3)$$
$$\bar{r}_0 = 1$$

where the differentiation of the encoder signal in r_k from equation (2.2) is approximated by the difference quotient $(incr_k - incr_{k-1}) / \Delta t$.

All other issues related to the implementation as a SIMULINK S-Function block correspond to what was said for the offset compensation.

3. Results from simulation and real-time implementation

The offset compensation and transducer gain correction from the preceeding section have been added as S-Function blocks to the conditioning subsystem for the tacho signal as shown in Figure 6. This is the content of the corresponding block from Figure 3.

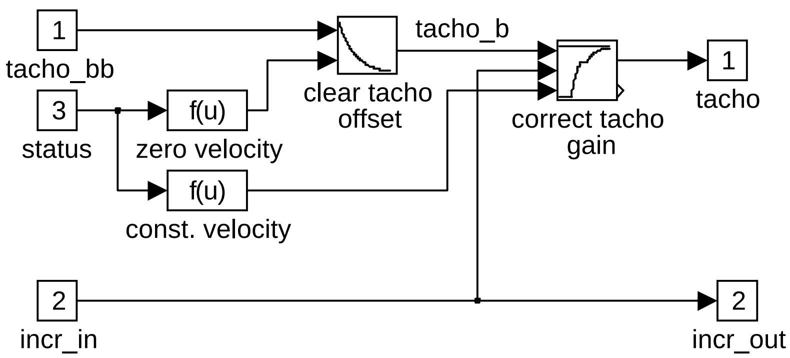

Fig. 6 *Signal conditioning subsystem for biased tacho signal*

Function blocks are used to generate boolean outputs for the expressions *ref_dot = 0* and *ref_dot = const* from the reference profile generator output *status,* which are needed to build the respective *condition* variables inside the S-Function blocks.

To show what is achieved from introducing the above signal conditioning subsystem to the control system, simulation was carried out for a tacho generator output offset voltage of 0,0045 V and a gain deviation of +12%. The reference signals applied to the controlled system by the reference profile generator block are shown in Figure 7.

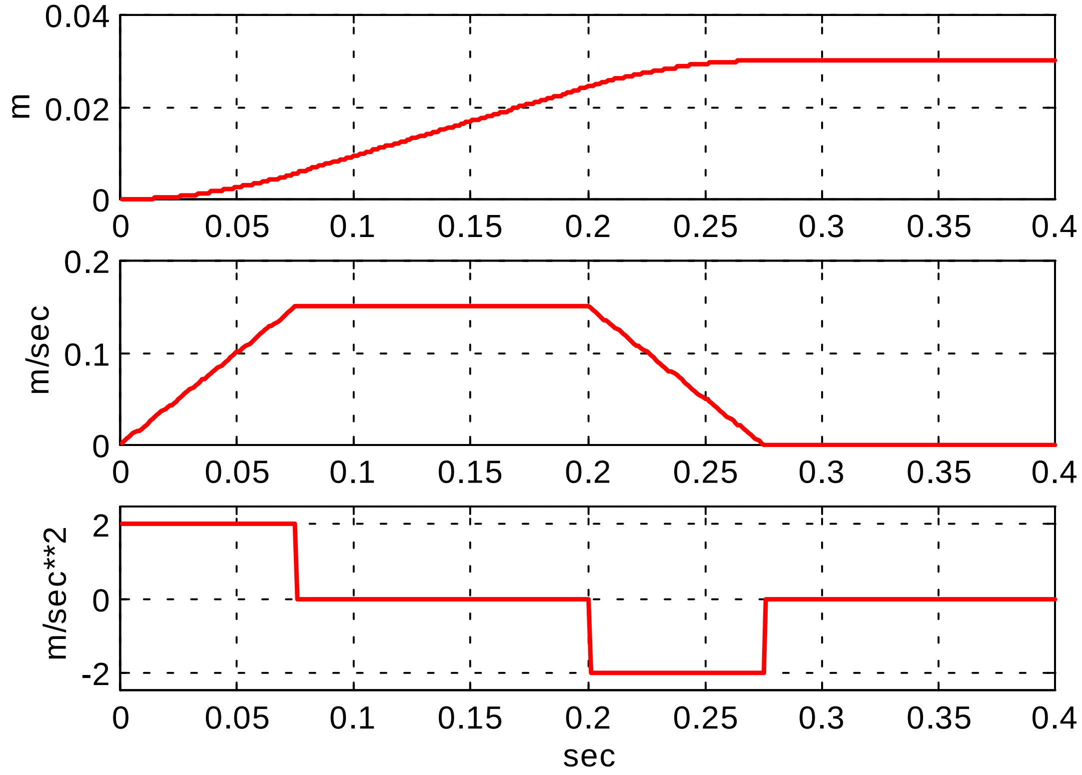

Fig. 7 *Carriage reference position (ref), velocity (ref_dot) and acceleration (ref_dotdot)*

Figure 8 presents the resulting time responses of the position error with and, for comparison, without conditioning of the tacho signal.

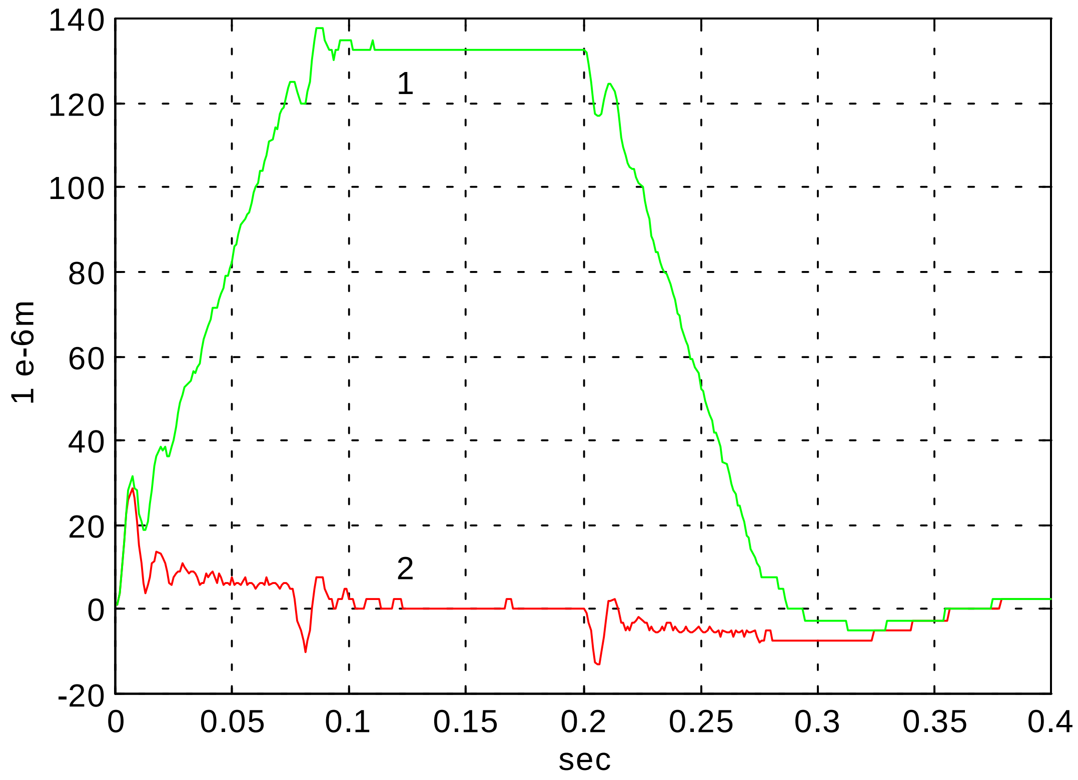

Fig. 8 *Simulated position error before (1) and after (2) tacho signal adaptation*

The simulation results are very close to what has been achieved in experimentation with the real EMPS. For this the control was implemented by automatic code generation using the Real-Time Workshop (RTW) and the Real-Time Interface (RTI) for the dSPACE DS1102 controller board, which are real-time extensions to SIMULINK [1].

The software tools TRACE and COCKPIT for data capture and display and experiment control have been used to acquire the following time responses during real-time execution of the controller [2].

Figure 9 shows the experimental results corresponding to the simulation results from Figure 8. For zero velocity (time > 0.3sec) the effect of the offset compensation is not apparent with this particular control, but it becomes more effective for larger offsets, and when controllers with smaller feedback gains are applied. Without tacho signal adaption (1) the position error of about 120µm due to the tacho generator gain deviation is unacceptable. With the signal conditioning subsystem after adaption (2) it is reduced to the range of 5µm during the constant velocity tracking phase.

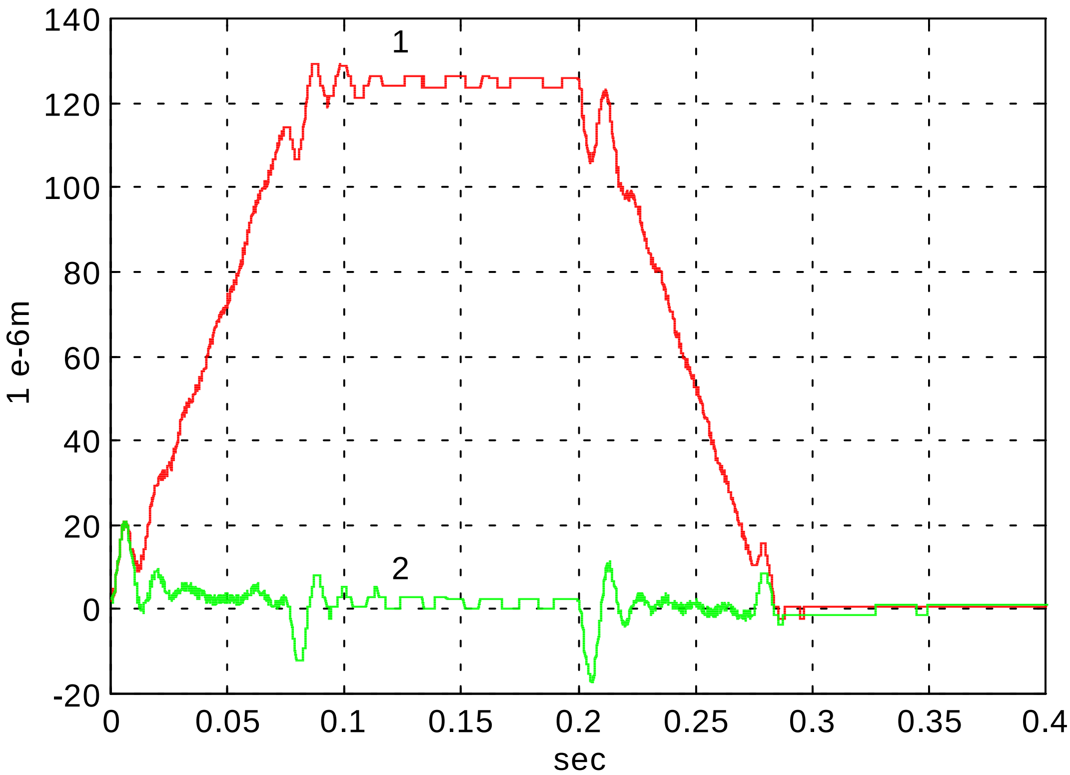

Fig. 9 *Measured position error before (1) and after (2) tacho signal adaption*

With the tacho signal conditioning, the position error is at its optimum in respect to the applied controller structure. Better results can be attained with a more sophisticated LQG approach [3]. For this approach the signal conditioning subsystem is even crucial to provide the observer with proper measurement signals, because usually the observer is not able to recognize offset and has been designed for nominal error-free transducer gains. The signal conditioning supports the observer to produce good estimates for missing sates variables, a pre-condition for a well-working LQG control.

Figures 10 and 11 show how the offset compensation voltage and the gain correction factor for the tacho signal adapt with different low pass filter time constants. This adaptation coincides with a continuous decreasement of the position error to the final results from time response 2 in Figure 9. Clearly visible with the horizontal courses in the time histories of Figures 10 and 11 are the time intervalls when updating of the variables *offset* from equation (2.1) and $\bar{r}$ from equation (2.3) is skipped because the corresponding *condition* variables are not true. The filter time constants T determine the approach of the individual variables to their steady-state values over different time horizons. A reasonable selection of the time constants is ten times the largest time constant of the closed-loop system. Also the waiting times to allow the system to settle should be far enough beyond this system time constant to preserve the closed-loop dynamics from control design.

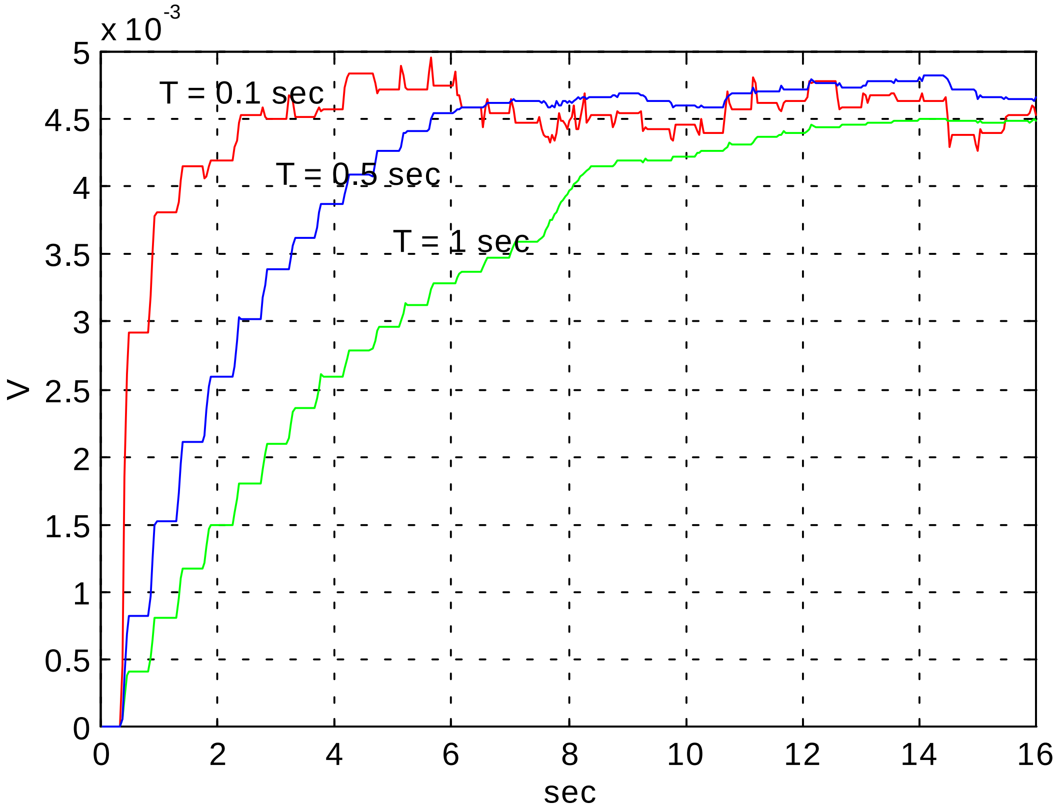

Fig. 10 *Measured offset voltage (waiting time 0,1 sec)*

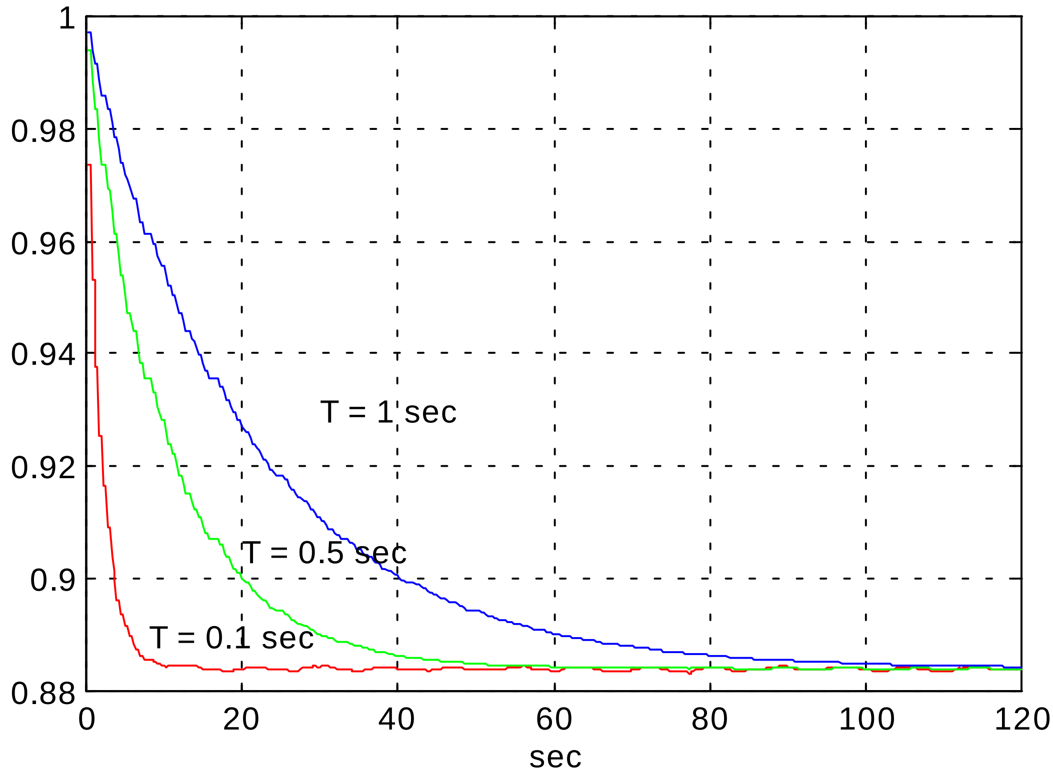

Fig. 11 *Measured gain correction factor* $\bar{r}$ *(waiting time 0,1 sec)*

4. Conclusions

A signal conditioning subsystem to compensate offset and bias from gain deviation on an analog tacho signal used for auxiliary feedback in a position control application has been succesfully designed and implemented. The real-time CAE-environment SIMULINK, RTW, RTI, DS1102, TRACE, and COCKPIT allow for a well documented, systematic, and seamless approach from the idea to the final concept proving in the experiment. Due to the modular design and validation process in the complete operational environment, for simulation as well as for experimentation, the presented analog tacho signal conditioning block became part of a library of reuseable blocks for high precision position control applications.

4. Literature

[1] MATLAB/SIMULINK/Real-Time Workshop User’s Guides,The Math Works, Inc., Nattick, Mass., USA, 1994

[2] Real-Time Interface, DS1102, TRACE, COCKPIT User’s Guides, dSPACE digital signal processing and control engineering GmbH, Paderborn, Germany, 1994

[3] H. Henrichfreise, "Practical issues on classical and modern control of electromechanical drive systems", Seminar PCIM '93 Conference, Nürnberg, Germany, June 21, 1993.