

Integrated Control and Circuit Simulation for a Motion Control System

P.Korondi, Budapest University of Technology and Economics; Budapest, Hungary
P.Bauer, Delft University of Technology, Mekelweg 4, 2628 CD Delft, Netherlands
P.J.van Duijsen Simulation Research, P.O. Box 397, NL-2400 AJ, Alphen aan den Rijn,
Netherlands

Keywords

Simulation, Variable structure control, chattering suppression

Abstract

In this paper the modelling of motion control system with Variable Structure System (VSS) theory using Matlab/Simulink and Caspoc is elaborated. The control is modeled in Simulink, while the power converter is modeled in Caspoc. This has advantages on both sides. Powerful toolboxes existing for Simulink can be used and the power electronics can be modeled in detail in the dedicated power electronics and drives simulation program Caspoc. The main contribution of this paper is the introduction of a powerful simulation tool, which can help in the keystone of most sliding mode designs, namely in the chattering free implementation. This approach and advantages of it are demonstrated on the motion control system. Experimental results of a DSP-controlled single-degree-of- freedom motion-control system are presented and compared with the simulation.

1. Introduction

To understand the advantages of an integrated simulation the strengths of the various existing programs have to be emphasized. Where Simulink [1] is thanks to the various toolboxes good in modelling and simulation of the control systems, it lacks support for power electronics simulation. Also the recently developed Power Systems toolbox didn't meet the goals many power electronics engineers have in mind. It lacks especially the component models, speed and accuracy of the simulation. Due to the numerical integration method and network calculation method used, the power toolbox suffers from the algebraic loop. It requires that a parasitic inductance and or capacitance be added to the circuit, which increases the order of the system.

On the other side Caspoc [2] was developed dedicated to the simulation and animation of power electronics and electrical drives. It is therefore much better suited for the simulation of switching circuits with highly non-linear switching models. However it is possible to combine both simulations through the open interfaces in both Simulink and Caspoc and such an approach is demonstrated in this paper. Combination of both simulation packages seems to be advantageous for educational purpose too. Students are on one side familiar with the Simulink from the basic curricula. Caspoc is very easy to handle and learn in a short time.

In Fig. 1 the coupling Simulink – Caspoc is depicted. In Matlab, a mathematical script is used to calculate parameters for the Variable Structure System. In Simulink, the block Caspoc2Simulink calls via a S-function the circuit simulator Caspoc at each time step. After one simulation time-step in Caspoc, the in Caspoc calculated detailed currents, voltages and/or other variables such as speed, torque or position, these are supplied back to the Simulink.

At the start of the investigation several Caspoc models were ready and the control was already simulated with Simulink. In the first iteration an averaged model of the system in Simulink was used.

Combination of both tools was the easiest and most advantageous step to do and in the second step Caspoc contains the detailed switching system.

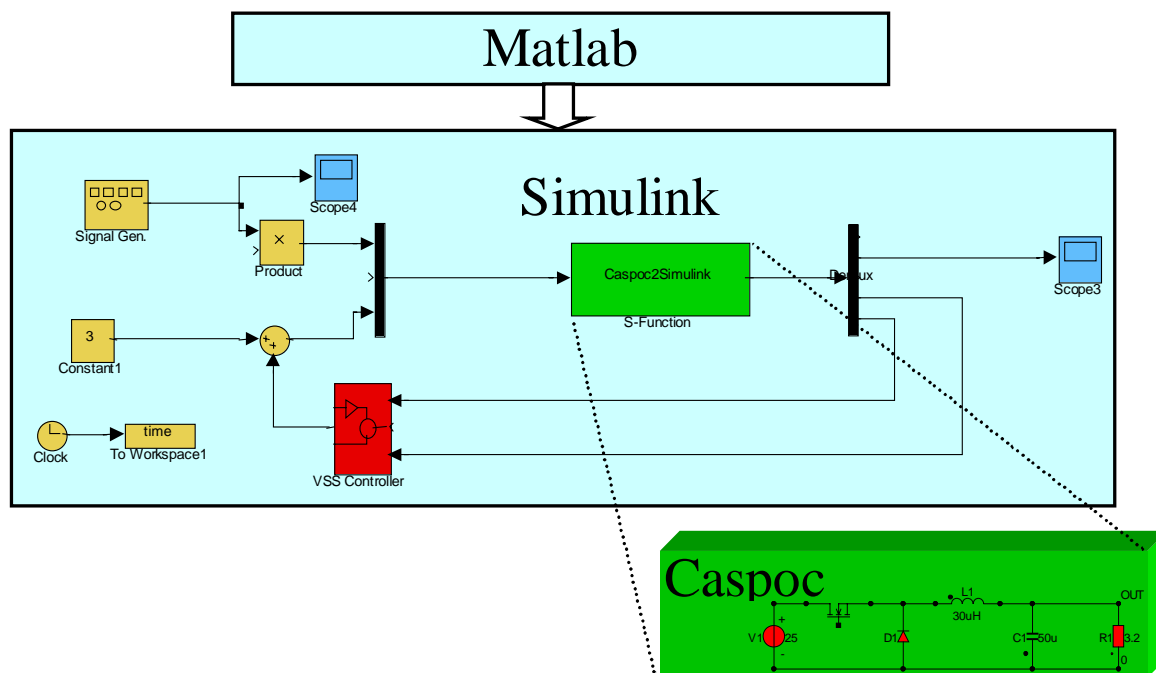


Fig. 1 Coupling between Matlab/Simulink and Caspoc

The organization of the paper is as follows: Section 2 summarises the theoretical background and the three main steps in designing of a sliding-mode controller, namely the surface design, the selection of the control law, and the chattering free implementation including the description of the experimental set up. Section 3 describe the simulation models. Section 4 analyses and compares the simulation and experimental results as the main contribution of this paper. Section 5 draws conclusions from the results presented in Section 4.

2. System description and theoretical background of the VSS

The design of a sliding-mode controller consists of three main steps. First is the design of the sliding surface, the second step is the design the control law which holds the system trajectory on the sliding surface, and the third and key step is the chattering-free implementation.

Design of the sliding manifold

The following linear time invariant (LTI) system is considered; first the reference signal is supposed to be constant and zero. The system is transformed to a regular form [4].

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} 0 \\ B_2 \end{bmatrix} u \quad \begin{matrix} x_1 \in R^{n-m} \\ x_2 \in R^m \\ u \in R^m \end{matrix} \quad (1)$$

The switching surfaces of the sliding mode, where the control vector components have discontinuities, can be written in the following form [1], where K is the control vector and σ a switching surface.

$$\sigma = x_2 + Kx_1 \quad \sigma \in R^m \quad (2)$$

When sliding mode occurs, and $x_2 = -Kx_1$ The design problem of the sliding surfaces can be regarded as a linear state feedback control design for the following subsystem:

$$\dot{x}_1 = A_{11}x_1 + A_{12}x_2 \quad (3)$$

In (3), x_2 can be considered as the input of the subsystem. A state feedback controller $x_2 = -Kx_1$ for this subsystem gives the switching surface of the whole VSS controller. In sliding mode

$$\dot{x}_1 = (A_{11} - A_{12}K)x_1 \quad (4)$$

Various linear control design methods based on state feedback are applicable to the design of the switching surfaces. Recently, many papers have appeared on optimal sliding surface design. In our approach a Linear Quadratic optimal sliding surface design is used [8].

Control law — Discrete-time sliding mode design

A kind of chattering is caused by the limited switching frequency of the control input. The robustness of continuous-time sliding mode control is obtained by high-frequency switching of high-gain control inputs. To adapt the sliding-mode philosophy for a digital controller, the sampling frequency should be increased compared to other types of control method. To solve this problem asymptotic reaching of the sliding manifold has been proposed in [2] to avoid commutation. In an alternative idea followed in [3] the samples of the system states belong to the sliding manifold after a finite number of sample steps. According to a definition, in the discrete-time dynamic system

$$x_{k+1} = F(x_k), x \in R^n \quad (6)$$

a discrete-time sliding mode takes place on the subset M of a manifold $\sigma(x) = 0, \sigma \in R^m (m < n)$ if there exists an open neighborhood U of this subset such that from $x \in U$ it follows $\sigma(F(x)) \in M$

According to this definition, the observer equation (1) and sliding surface (3) should be discretized at each sampling instant.

$$x_{k+1} = A_d x_k + B_d u_k \quad (7)$$

$$\sigma_k = \Lambda_d x_k \quad (8)$$

It follows from the definition that

$$\sigma_{k+1} = 0 \quad (9)$$

for any $x_k \in U$ The discrete-time sliding mode exists if matrix $\Lambda_d B_d$ is invertible and control u_k is designed to satisfy (9). By analogy with continuous-time systems, the solution of (9) is referred to as “equivalent control”.

$$u_{eqk} = (\Lambda_d B_d)^{-1} \Lambda_d (x_{refk+1} - A_d x_k) \quad (10)$$

This type of discrete-time sliding mode control law involves prediction. Knowledge of the model is necessary. The purpose of the simulation is to verify the developed theory on the selected system. As mentioned for the control part simulink is used and for system simulation Caspoc.

Chattering free implementation

The experimental system consists of a conventional DC servo gear motor with encoder feedback and variable inertia load coupled by a relatively rigid shaft, as shown in Fig. 2. The controller is implemented using a DSP as the computation engine.

In the course of control design, a reduced-order model is used, in which the armature inductance and the flexibility of the shaft are ignored. The state variables are the shaft position, θ and the shaft angular velocity, ω , the control signal u is the motor voltage. The effect of $mass_d$ is considered as a disturbance. The model calculated from the nominal parameters of the system is as follows:

$$\begin{pmatrix} \dot{\theta} \\ \dot{\omega} \end{pmatrix} = \begin{pmatrix} 0 & 1 \\ 0 & -17.3 \end{pmatrix} \begin{pmatrix} \theta \\ \omega \end{pmatrix} + \begin{pmatrix} 0 \\ 5.9 \end{pmatrix} u \quad (11)$$

Since a second-order model is applied, the sliding “surface” is a sliding line and its dynamics can be described by one pole P , which is the reciprocal of the time constant of the sliding mode dynamics. The sliding surface is carefully designed (i.e. P is selected according to [8]) to satisfy both fast response and vibration suppression.

$$T=1/P=1/15 \text{ s}$$

To avoid the excitation of the resonance modes, relatively high chopper switching frequency is selected, and it is twenty times higher than the controller sampling frequency

$$T_{\text{sampling}}=1000\mu\text{s} \quad T_{\text{chopper}}=50\mu\text{s}.$$

3. Simulation model

In Fig. 2 the power electronics circuit with electrical DC machine and mechanical load is modelled. The inverter is modelled in detail containing models for the used mosfets. The output of the inverter is connected to the DC machine, which in this case is a simple shunt machine. The DC machine is connected to the drive train consisting of a gearbox, flexible shaft and rotating load. Position and speed of the total drive is measured on both sides of the flexible shaft. Parameters for the components come from a Caspoc database, so only the types of mechanical components have to be defined. The control of the mosfets is done using a control block for which the switching frequency and the duty cycle are provided by the control in Simulink. The measured DC link voltage machine current as well as the speed and position of the drive train are exported to Simulink using the ToSlnk blocks. The control variables from Simulink are imported using the FromSlnk blocks. The freedom to define and model the power electronics circuit, its connection to electrical machines and mechanical drive trains are the clear advantages of a program like Caspoc. After creating the model in Caspoc, one can continue to develop the control in Simulink.

In Fig. 3 the model for Simulink is displayed. In this model the Variable Structure System (VSS) is modelled twice. First (black/white) completely in Simulink and second (colored) as a integrated Simulink/Caspoc model. The results are displayed in the same scopes for comparison. In the first model in Simulink an averaged modeled is used to mimic the power converter. In the second model the complete power converter with mosfets is modeled on the circuit level. The Caspoc2Simulink block represents the model of the power converter with electrical machine and drive train in Caspoc. Mux and Demux blocks are used for the communication between Caspoc and Simulink. The control signal from the Simulink model is fed into the ref_gen1 and VSS_Controller1 blocks. The control signal from the VSS controller is then scaled to the duty cycle [0..1] which is fed to Caspoc. The switching frequency is constant. The results from the Simulink block (Two Mass) and the results from

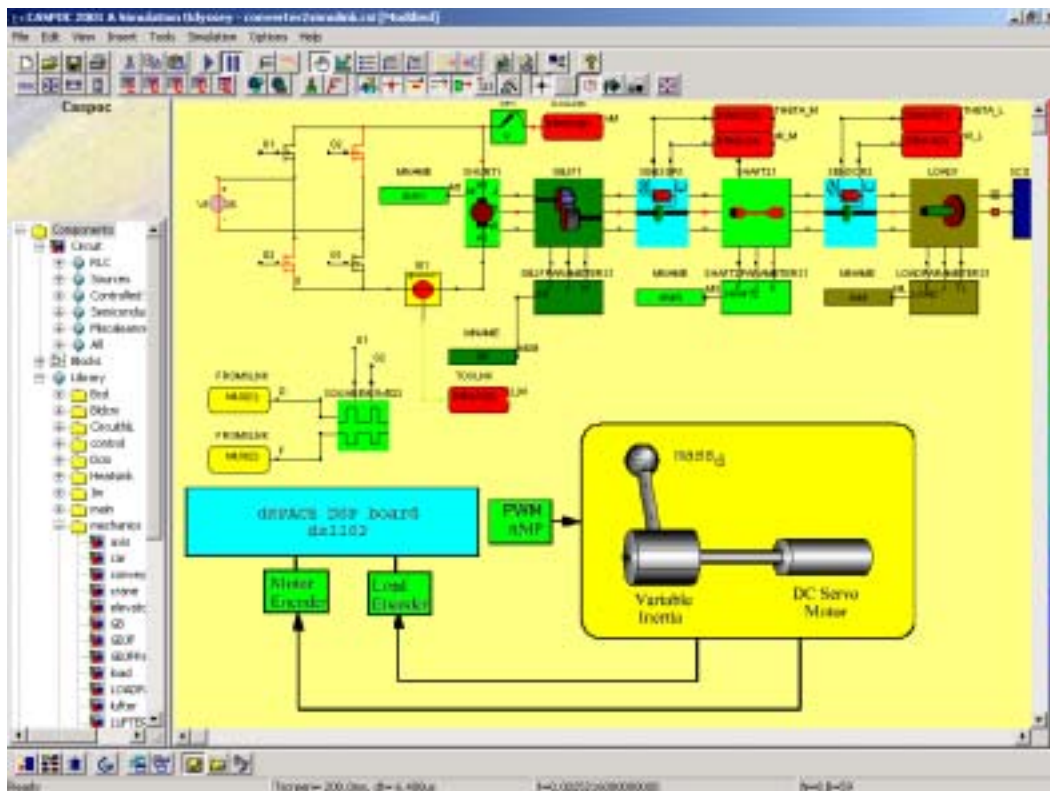


Fig. 2 Motion Control System with Power converter, DC machine and two-mass mechanical load.

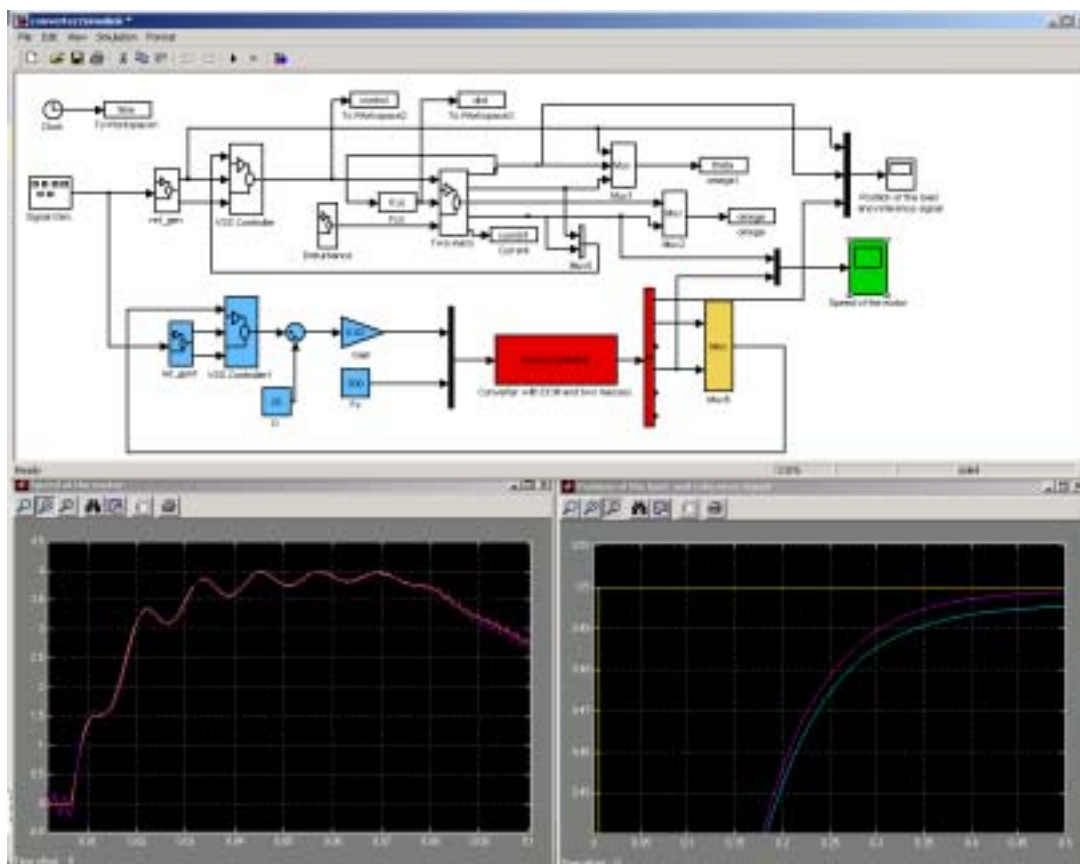


Fig. 3 Simulink model of a Variable structure system example and simulation results

the Caspoc model (Converter with DCM and two masses) are displayed in the scopes on the bottom of the Fig. 3. The scope on the left shows the speed of the machine, while the scope on the right side shows the position of the load. In case of the Simulink averaged model, the speed is smoother (yellow line), and there is an additional oscillation (red line) in case of integrated Simulink-Caspoc simulation. Also the error in the position becomes larger for lower switching frequencies (blue line). It demonstrates that the integrated Simulink-Caspoc simulation presents more realistic result than a Simulink average model simulation. A detailed analysis is presented in the next Session.

4. Comparison of Simulation and Experimental Results

Sets of two basic types of simulation results are compared.

- a. Averaged Simulink model
- b. Integrated Simulink/Caspoc model with different switching frequencies.

The reference is a pulse train in all cases. The simulation results are presented using the *plot* command from Matlab. In all cases, the time functions of the reference and the angular position of the load, the phase trajectory, the control action and the shaft torque are shown for 6 seconds of the simulation. The Fig. 4 shows the time functions of the reference and the angular position of the load. Three of the four plots seem to be similar. In case of Caspoc/Simulink simulation with the switching frequency of 250 Hz (see in Fig. 6. d.), the angular position cannot reach its reference value. In another words, the effect of the disturbance-inverted-pendulum cannot be compensated.

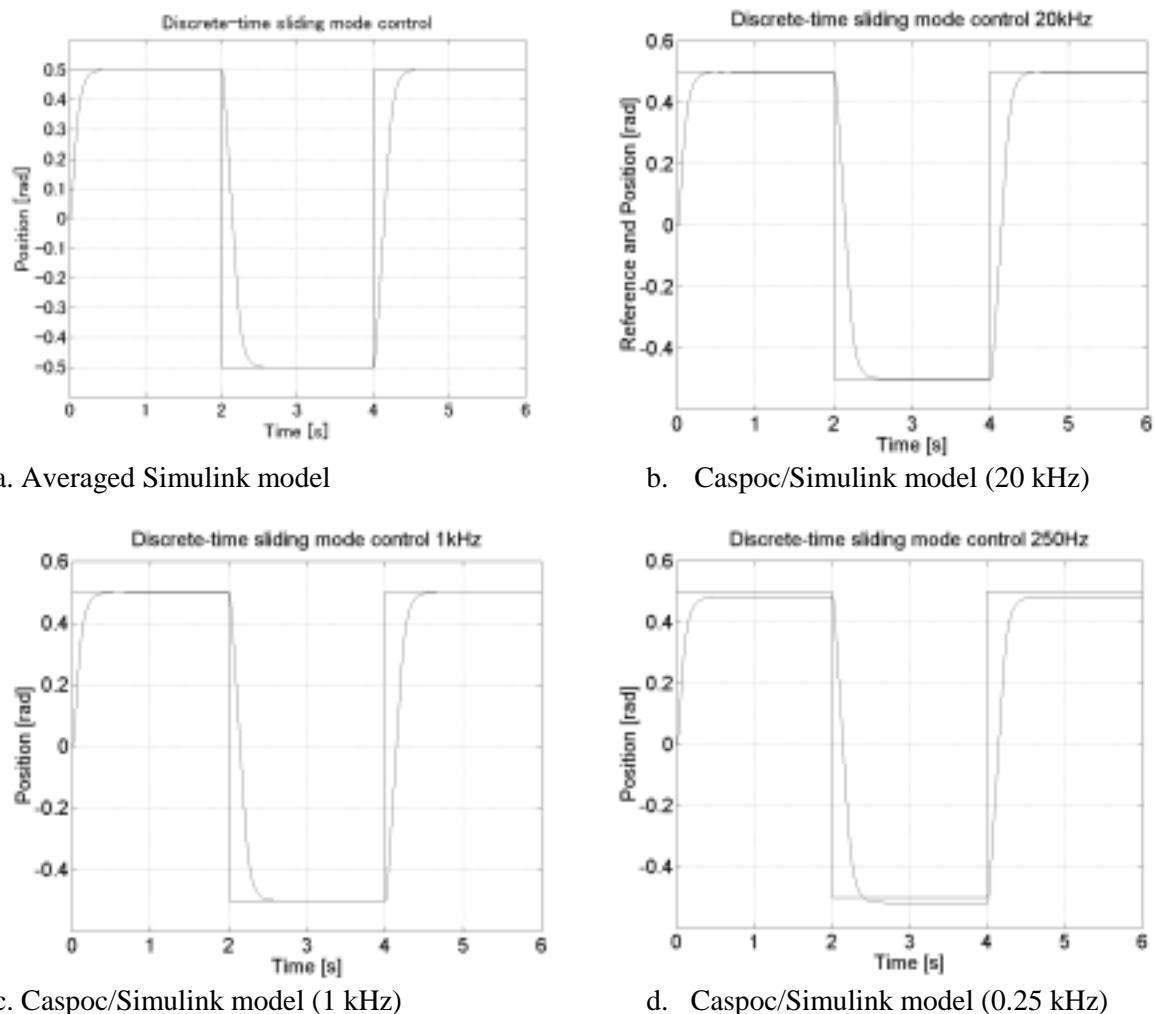


Fig. 4. Time functions of the reference and the angular position of the load

Fig. 5 explains the error observed in Fig. 4. d. If u_{eqk} is small in (10) and the sampling frequency is big than σ_k might chatter around the manifold $\sigma=0$ as shown in Fig. 5, where T^k denotes the time of k -th sampling. Because of the alternating u_{eqk} the average control is 0, even if the ideal $u_{eqk} \neq 0$. Fig. 6 shows the trajectory in the four cases. In case of Caspoc/Simulink simulation with the switching frequency of 250 Hz (see in Fig. 6. d.), the trajectory does not go through the origin, presenting a similar error as observed in Fig. 4. d.

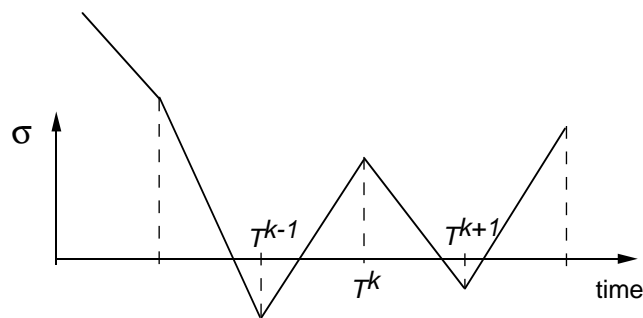
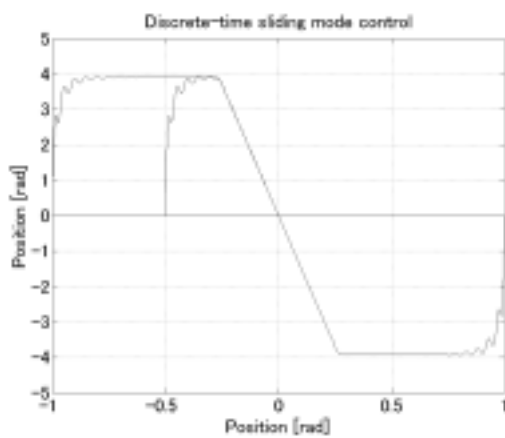
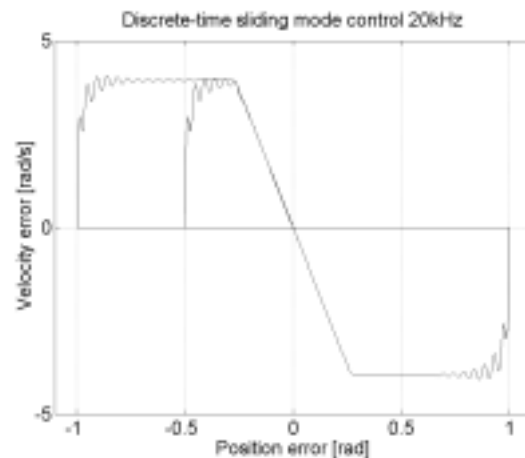


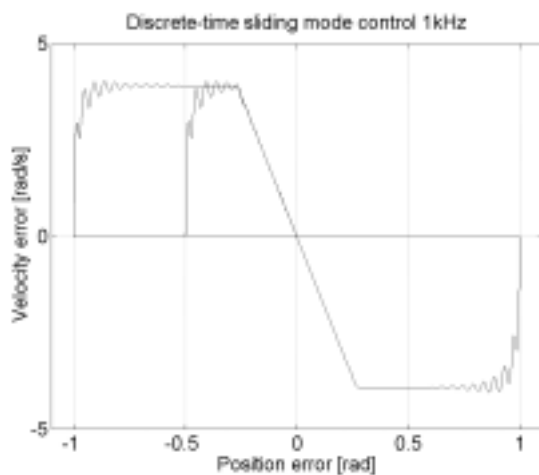
Fig. 5 Discrete-time chattering phenomenon



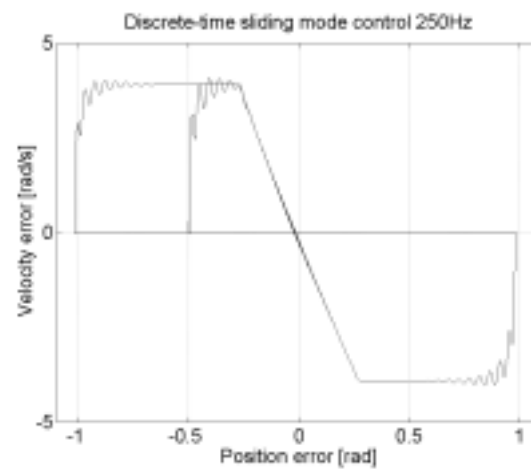
a. Averaged Simulink model



b. Caspoc/Simulink model (20 kHz)



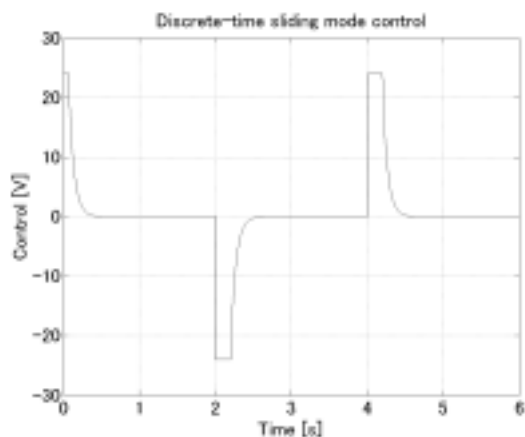
c. Caspoc/Simulink model (1 kHz)



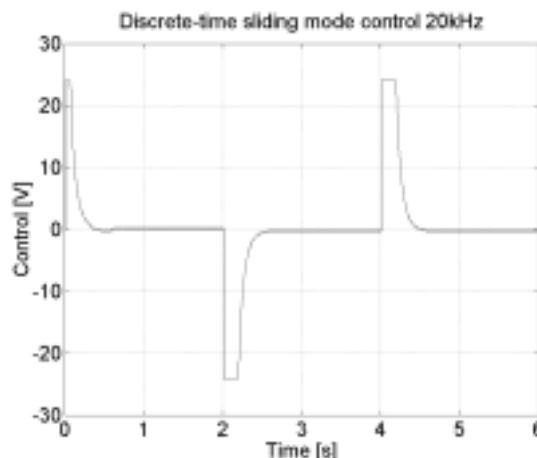
d. Caspoc/Simulink model (0.25 kHz)

Fig. 6. Trajectories

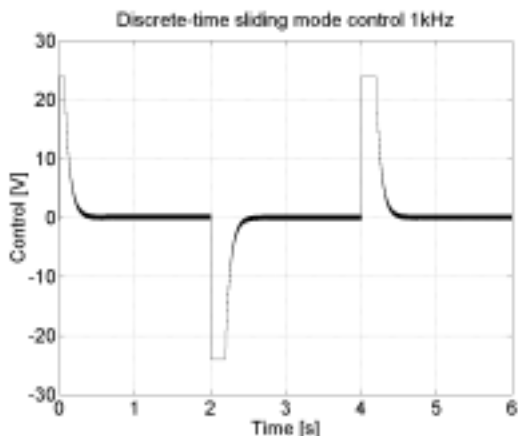
Fig. 7. shows the control signals. As it is expected, in case of the averaged Simulink model, the control signal is really smooth. The smaller is the switching frequency, the bigger is the control action. This effect is more significant in the shaft torque (see in Fig. 8). It is well known, that the one of the main source of the chattering is the unmodelled dynamics of the controlled plant [9]. In this simple motion control system, the unmodelled shaft flexibility might cause dangerous chattering depending on the actual application [9]. In other words, the switching frequency can be carefully selected with the help of the proposed integrated simulation tool for actual requirements of the actual implementation.



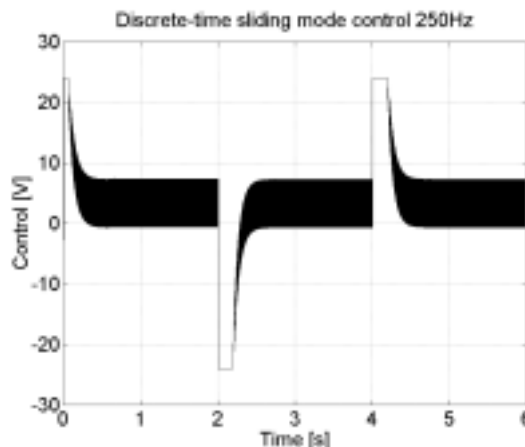
a. Averaged Simulink model



b. Caspoc/Simulink model (20 kHz)

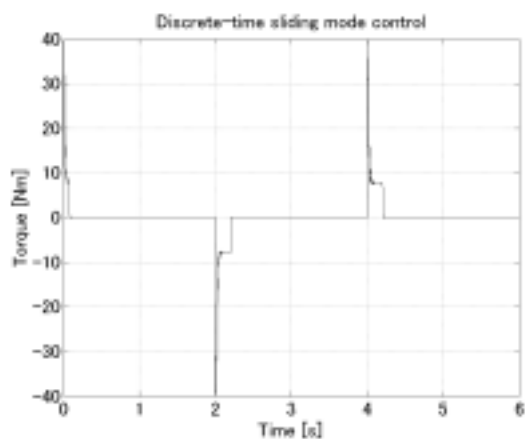


c. Caspoc/Simulink model (1 kHz)

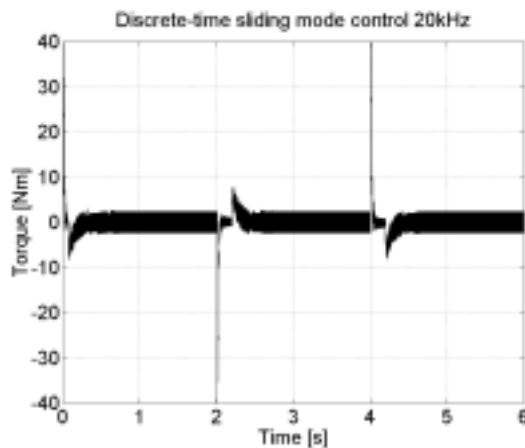


d. Caspoc/Simulink model (0.25 kHz)

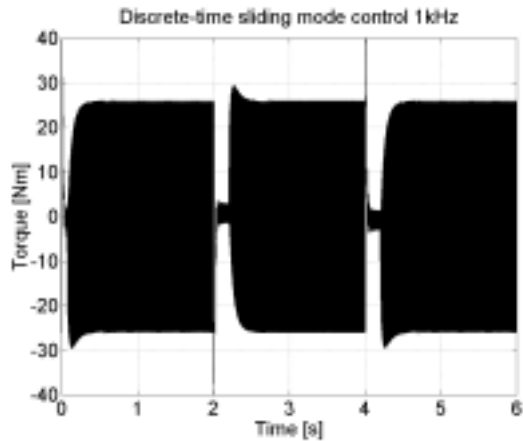
Fig. 7. Control signals



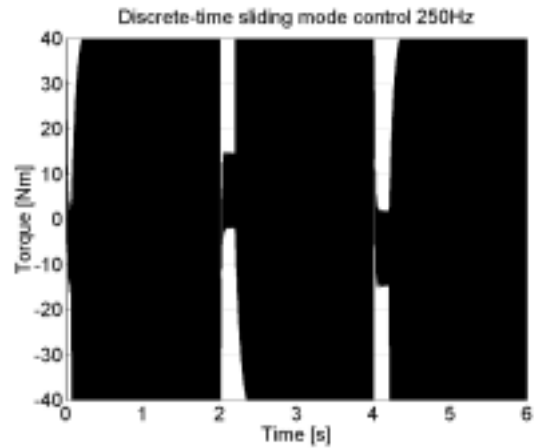
a. Averaged Simulink model



b. Caspoc/Simulink model (20 kHz)



c. Caspoc/Simulink model (1 kHz)



d. Caspoc/Simulink model (0.25 kHz)

Fig. 8 Shaft torques

Experimental results

The experimental results are shown in Fig. 9, Fig. 10 and Fig 11. In the Fig. 9 the time functions of the reference and the angular position of the load, in Fig. 10 the phase trajectory, and in Fig. 11 the control action are shown. As it was anticipated from the integrated Simulink/Caspoc simulation results, a constant switching frequency of 20 kHz ensures a chattering free implementation of sliding mode control.

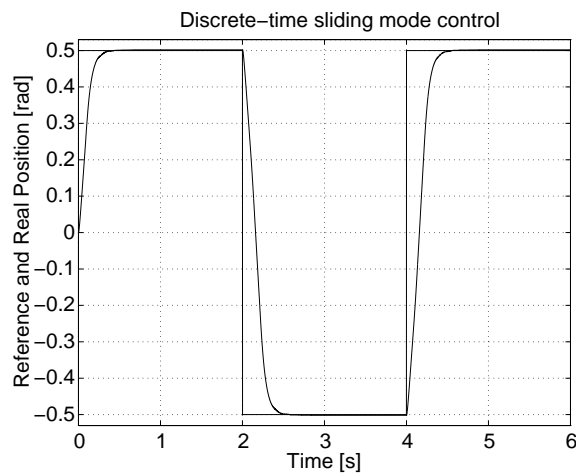


Fig. 9 Experimental result, position

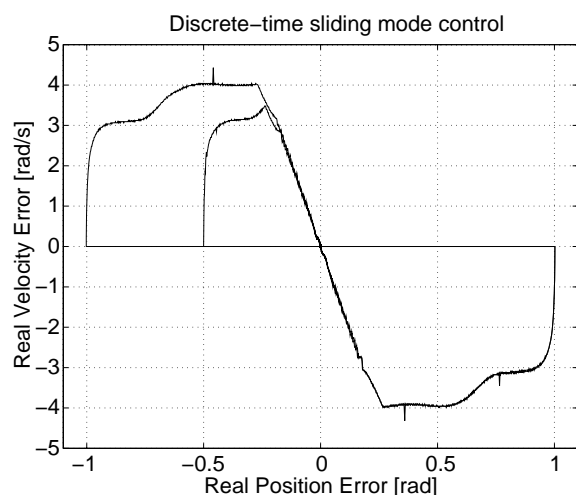


Fig. 10 Experimental result, trajectory

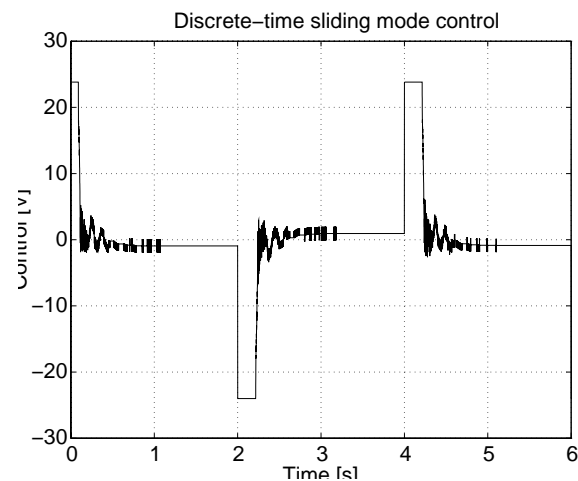


Fig. 11 Experimental result, control signal

5. Conclusion

This paper discusses integrated simulation of a motion control system with VSS control. It demonstrates that the use of two different packages can be advantageous and lead to a complex system simulation with a sophisticated control. Some researchers think, that despite the theoretical superb performance of a closed loop system in sliding mode, it has limitations in practice due to the need for high sampling frequency to reduce the high frequency oscillation phenomenon about the sliding mode manifold, collectively referred to as “chattering”. In most of the experimental works involving sliding mode, the effort spent on understanding the theoretical basis of sliding mode control are generally minimized, while a great deal of energy were invested in empirical techniques to reduce chattering. The averaged Simulink model might hide an important source of chattering and the integrated Caspoc-Simulink model enables a deeper view into the operation of a system controlled in sliding mode. The integrated simulation can help to find the optimal or lowest switching frequency for the real systems. Theoretical results are confirmed with the practical experience.

References

- [1] Matlab, The MathWorks Inc, www.mathworks.com
- [2] Simulation Research, Users Guide Caspoc 2003, www.caspoc.com
- [3] Utkin, V.I., and K.D.Young, Methods for Constructing Discontinuous Planes in Multidimensional Variable Structure Systems, Automation and Remote Control, Vol. 31, No.10, pp.1466-1470, 1978
- [4] Furuta, K., “Sliding Mode Control of a discrete system,” System Control Letters}, Vol. 14, pp.~145-152, 1990.
- [5] Utkin, V.I. S.V. Dracunow: On Discrete-time Sliding Modes Control IFAC Conference on Nonlinear Control Capry, 1989.
- [6] Luk'uyanov A. G., Utkin V.I.: Method of reducing equations of dynamic systems to regular form, Automation and Remote Control, 42, (P.1), pp.413-420,1981.
- [7] Utkin V.I.: Variable Structure Control Optimization, Springer-Verlag. 1992.
- [8] P.Korondi, H.Hashimoto; Sliding Mode Design for Motion Control (12 pages) Studies in Applied Electromagnetics and Mechanics Vol. 16. ISBN 90 5199 487 7, IOS Press 2000.
- [9] P.Korondi, H.Hashimoto, V.Utkin “Direct Torsion Control of Flexible Shaft based on an Observer Based Discrete-time Sliding Mode” IEEE Trans. on Industrial Electronics vol. IE- no.2. pp. 291-296, 1998.