

Application of Different State Variable Estimators in Control Structures of Two-mass Drive System

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Abstract – The paper presents issues relevant to control of a two-mass system. In order to provide effective vibration suppression, there is a need to apply additional feedback in control structures. Different methods of state variable estimation were considered, namely the simple estimator, the Luenberger observer and the Kalman filter. The quality of variable estimation in an open-loop and a closed-loop system with the use of these methods was compared. The laboratory set-up used for the experimental verification of the developed control structures was briefly described. All methods of variable estimation were tested in an open and a closed-loop system. Some experimental results for classical PI speed control structure with additional feedbacks and for the structure with the state controller are presented.

Index terms – DC drive, elastic joint, estimation techniques, PI speed controller, state controller

I. INTRODUCTION

In some industrial applications like rolling mill drives, the mechanical part of the system has very low resonant frequency, because of a long shaft between the motor and the load machine. So, especially in the drive systems with high performances of the speed and torque regulation, the motor speed is different from the load speed during transients. The speed difference results in the coupling shaft stresses, which influence this mechanical coupling in a negative way. Additionally, speed oscillations cause decrease in the quality of the rolling material and can influence the stability of the control system [1-6]. The simplest method to eliminate the oscillation problem (occurring while the reference speed changes) is a slow change of reference velocity. But it causes the decrease of the drive system dynamics and does not protect against oscillations resulting while disturbance torque changes. Some methods of this problem solving are reported in technical papers. The most advanced techniques, ensuring very good performances of the system, are based on special control structures with additional feedbacks from such state variables as torsional torque, load speed and/or disturbance torque. But the direct feedbacks from these signals are very often impossible, because additional measurements of these mechanical variables are difficult, cost effective and reduce the system reliability. Thus special systems for state variables estimation are necessary, such as estimators, state observers or state filters.

In the paper comparative tests of three methods of variable estimation were presented. The quality of variable estimation using the simple estimator, the Luenberger observer and the Kalman filter were compared. Simulation tests of the control system with PI or state speed controllers and different types of state variables estimation were carried out. The laboratory set-up was briefly described and experimental results were demonstrated.

II. THE CONTROLLED DRIVE SYSTEM

A: The mathematical model of the drive system

In the paper a commonly-used model of the DC drive system with the resilient coupling was considered. The system is described by the following state equations (in per unit system), with nonlinear friction neglected:

$$\frac{d}{dt} \begin{bmatrix} i_a(t) \\ \omega_1(t) \\ \omega_2(t) \\ m_s(t) \end{bmatrix} = \begin{bmatrix} -\frac{1}{T_e} & -\frac{K_t \Psi_f}{T_e} & 0 & 0 \\ \frac{\Psi_f}{T_l} & 0 & 0 & -\frac{1}{T_l} \\ 0 & 0 & 0 & -\frac{1}{T_2} \\ 0 & \frac{1}{T_c} & -\frac{1}{T_c} & 0 \end{bmatrix} \begin{bmatrix} i_a(t) \\ \omega_1(t) \\ \omega_2(t) \\ m_s(t) \end{bmatrix} + \begin{bmatrix} \frac{K_t}{T_e} \\ 0 \\ 0 \\ 0 \end{bmatrix} [u_t] + \begin{bmatrix} 0 \\ 0 \\ -\frac{1}{T_2} \\ 0 \end{bmatrix} [m_o] \quad (1)$$

where: ω_1 - motor speed, ω_2 - load speed, i_a - armature current, K_t - gain factor of the motor, Ψ_f - excitation flux, m_s - shaft (torsional) torque, m_o - disturbance torque, T_l - mechanical time constant of the motor, T_2 - mechanical time constant of the load machine, T_c - stiffness time constant. Parameters of the analysed system are following: $T_l = 230\text{ms}$, $T_2 = 230\text{ms}$, $T_c = 2.6\text{ms}$, $\Psi_f = 1$, $K_t = 7.4$.

B: The speed control structures

The first considered speed control of the drive system has the most widely used cascade structure shown in Fig. 1

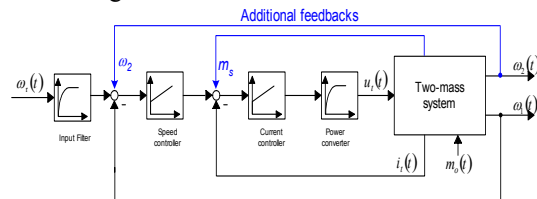


Fig.1. The PI control structure with additional feedbacks

It consists of two major loops. The inner control loop encloses the current controller, the power converter and the electromagnetic part of the motor. It is designed to provide sufficiently fast torque control and very often is approximated by a first order filter. The PI current controller is usually adjusted according to the well known modulus criterion. The outer control loop includes: the mechanical part of the drive, the speed sensor and the PI controller typically adjusted according to the symmetry criterion or poles placement method [2]. The classical structure works well only for some inertia ratio (T_2/T_1) of the two-mass system. In the case of low mechanical time constant of the load machine, transients of the system are not proper. In order to damp torsional vibrations effectively additional feedback from one of the following variables: torsional torque, derivative of torsional torque or from speed of load machines needs to be applied. The structure with one additional feedback can suppress the torsional vibrations effectively but the system has only one resonant frequency depending on mechanical parameters of the system. It can be too low in some applications.

If there is a requirement to have very fast response of the drive system, then the state feedback structure can be used, which general scheme is presented in Fig. 2.

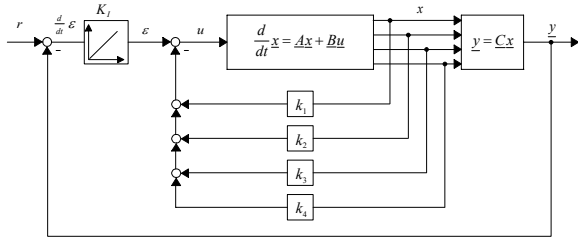


Fig.2. The state feedback control structure

The performances of the system depend on closed-loop poles locations. The locations of feedback coefficients can be calculated using Ackerman formula [7]. Placing the closed-loop poles more to the left of the original plant poles, results in the faster responses of the system. In this structure there is possible to have very fast speed response, but the information about all states is needed.

III. METHODS OF MECHANICAL STATE VARIABLES ESTIMATION

A. Simple estimator of torsional torque

If the requirement concerning of the system dynamics is connected only with a good suppression of torsional vibrations, then PI control structure with one additional feedback from torsional torque or its derivative can be used. The simplest method to obtain information about the required variable is to apply torsional torque estimator, described by the following equation:

$$m_s = m_e - sT_1\omega_1 \quad (2)$$

where: $s = d/dt$.

The scheme of such estimator is presented in Fig. 3.

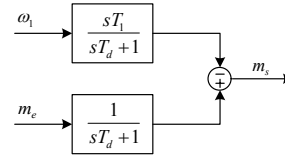


Fig.3. The block diagram of torsional torque estimator

The T_d time constant is used to ensure a real derivation of the speed signal; its value depends on the noise level in the real system and it should be as small as possible. The accuracy of the estimator depends only on the mechanical time constant of the motor.

B. State observers

The state feedback control structure requires information about all mechanical state variables of the drive system, i.e. torsional torque and load speed. Additionally, in some cases there is a need to apply additional feedback from estimated load torque, to improve the drive speed response to the load torque changes. The commonly used methods to obtain this information are Luenberger observer and Kalman filter.

1) Mathematical model of the extended full-order

Luenberger observer for two-mass drive system

The electromagnetic torque m_e of the motor (proportional to the armature current) was used as a control input of the estimation system and the angular speed of the motor was taken as the output value. Hence, the results of this work can be applied to any kind of electrical motor with high performance torque control.

For the linear dynamical system described by the linear state equation:

$$\begin{aligned} \frac{d}{dt} \underline{x}(t) &= \underline{A}\underline{x}(t) + \underline{B}u(t) \\ \underline{y}(t) &= \underline{C}\underline{x}(t) \end{aligned} \quad (3)$$

the full-order Luenberger state observer is described by the following state equation:

$$\begin{aligned} \frac{d}{dt} \hat{\underline{x}}(t) &= \underline{A}\hat{\underline{x}}(t) + \underline{B}u(t) + \underline{K}[\underline{y}(t) - \hat{\underline{y}}(t)] \\ \hat{\underline{y}}(t) &= \underline{C}\hat{\underline{x}}(t) \end{aligned} \quad (4)$$

In the case of the drive system with elastic joint, the state vector of the drive system was extended by the load torque value, to obtain the estimation of all mechanical state variables of the system:

$$\underline{x} = [\omega_1 \quad \omega_2 \quad m_s \quad m_o]^T \quad (5)$$

The motor electromagnetic torque and speed were used as input and output variables, respectively.

$$\underline{u} = m_e, \quad \underline{y} = \omega_1 \quad (6)$$

Thus the state, control and output matrices of this extended Luenberger observer are as follows:

$$\underline{A} = \begin{bmatrix} 0 & 0 & -\frac{1}{T_{m1}} & 0 \\ 0 & 0 & \frac{1}{T_{m2}} & -\frac{1}{T_{m2}} \\ \frac{1}{T_c} & -\frac{1}{T_c} & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \quad \underline{B} = \begin{bmatrix} \frac{1}{T_{m1}} \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

$$\underline{C} = [1 \ 0 \ 0 \ 0] \quad (7)$$

The gain matrix \underline{K} (set to $\underline{K}=[12 \text{ e-}7 \text{ e-}9 \text{ 182}]$) was determined using genetic-gradient algorithm (GGA) described briefly in [8], using special form of the cost function [9], to provide robustness of the estimator to parameter changes of the mechanical system.

2) Mathematical model of the Kalman filter for two-mass drive system

The same extended state equations (7) were used for the Kalman filter design. According to the theory of Kalman filtering, it was assumed that a system is disturbed with Gaussian white noises, which represent process and measurement errors ($w(t), v(t)$). The system is thus described:

$$\begin{aligned} \frac{d}{dt} \underline{x}(t) &= \underline{A} \underline{x}(t) + \underline{B} \underline{u}(t) + \underline{w}(t) \\ \underline{y}(t) &= \underline{C} \underline{x}(t) + \underline{v}(t) \end{aligned} \quad (8)$$

where: $\underline{A}, \underline{B}, \underline{C}, \underline{x}, \underline{y}, \underline{u}$ – as (12)–(14).

After discretisation of Eq.8 with T_s sampling step, the state estimation using the Kalman filter algorithm is calculated:

$$\hat{\underline{x}}(k+1/k+1) = \hat{\underline{x}}(k+1/k) + \underline{K}(k+1)[\underline{y}(k+1) - \underline{C}(k+1)\hat{\underline{x}}(k+1/k)] \quad (9)$$

where the gain matrix is obtained by the following numerical procedure:

$$\begin{aligned} \underline{P}(k+1/k) &= \underline{A}(k)\underline{P}(k/k)\underline{A}(k)^T + \underline{Q} \\ \underline{K}(k+1) &= \underline{P}(k+1/k)\underline{C}(k+1)^T [\underline{C}(k+1)\underline{P}(k+1/k)\underline{C}(k+1)^T + \underline{R}]^{-1} \\ \underline{P}(k+1/k+1) &= [\underline{P}(k+1/k) - \underline{K}(k+1)\underline{C}(k+1)]\underline{P}(k+1/k) \end{aligned} \quad (10)$$

with state and measurement covariance matrices \underline{Q} and \underline{R} (set to $\underline{Q} = \text{diag}[0.25, 35, 3\text{e-}12, 1\text{e}4]$, $\underline{R} = [75]$).

The suitable choice of covariance matrices is rather a difficult task, usually solved by trial and error. So, in this paper the same GGA was used for solving the optimisation process.

IV. RESULTS OF SIMULATIONS

A. Open loop system

In simulation and experimental tests the motor was fed by the AC/DC power converter with switching frequency 5kHz. The sampling step used for the rotor speed measurement in the open-loop system was 0.2 ms.

In Fig.4 simulated transients of real and estimated torsional torques m_s, m_{se} , load speed ω_2, ω_{2e} , load torque m_o, m_{oe} for both estimators are presented, in the case of nominal drive parameters. As follows from presented test results, both estimation methods worked in a proper way. The Luenberger observer had slightly

larger estimation errors of all variables; however, its computational algorithm is far simpler, hence a cheaper microprocessor can be used in practical realisation of the drive control system.

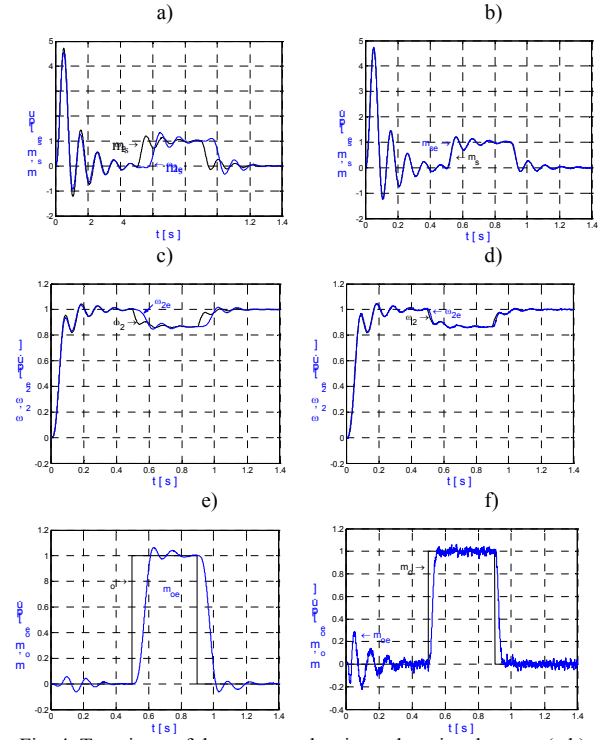


Fig. 4. Transients of the motor and estimated torsional torque (a,b), load speed (c,d), load torque (e,f) for nominal drive parameters, using Luenberger observer (a,c,e) and the Kalman filter (b,d,f)

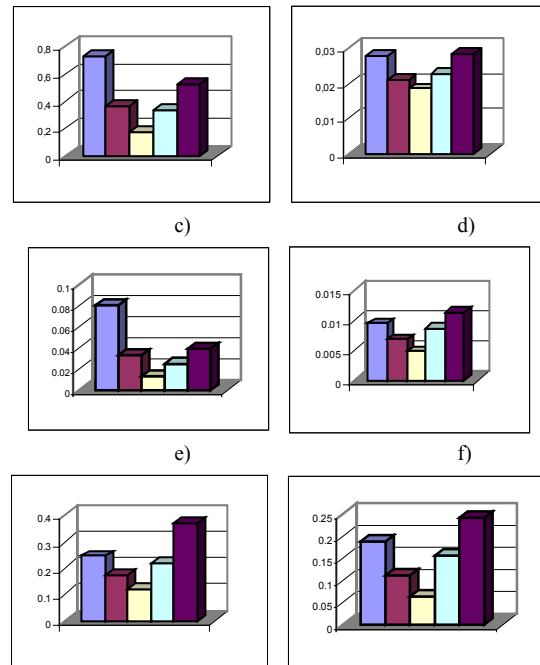


Fig. 5. Estimation errors of torsional torque (a,d), load speed (b,e) and load torque (c,f) for changed load inertia: from left: 50%, 75%, 100%, 150% and 200% of nominal value, using Luenberger observer (a,c,e) and Kalman filter (b,d,f)

The estimation errors were calculated according to the Eq. 11 and presented in this chapter:

$$\Delta_j = \frac{\sum_{i=1}^N |x_j - \hat{x}_j|}{N}; \quad (11)$$

where: x_j - actual motor variable, \hat{x}_j - estimated variable, N - number of samples.

The load inertia was changed to check the sensitivity of Luenberger observer and Kalman filter. In Fig.5 an example of errors calculated according to Eq. 11 for both observers are presented in the case of load inertia changes. It is seen that for the same range of parameter changes, the Kalman filter presents much lower estimation errors and better dynamics in the case of fast step changes of the motor speed or load torque.

B. Closed loop system

In this chapter dynamical performances of two analysed structures were presented. Fig. 6 shows transients of variables in PI control structure with additional feedback from torsional torque (a,b) ($K_p=26$, $K_I=384$, $k_I=0,96$) and derivative of torsional torque (c,d), ($K_p=12$, $K_I=136$, $k_2=0,021$) respectively. Both systems have been working with the simple estimator (2). Transients in the control structure with additional feedback from torsional torque are faster, the speed settling time and the overshoot are smaller. The damping coefficient in both structures was set to 0.7.

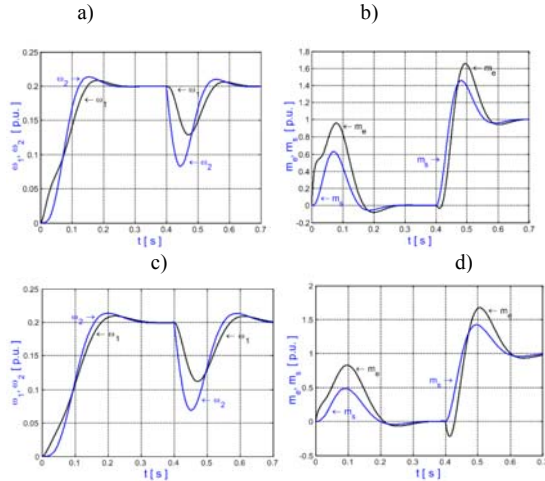


Fig. 6. Transients of state variables of the system with PI control structure and additional feedback from the torsional torque (a,b), derivative of torsional torque (c,d)

Fig.7 shows transients of the drive variables in the controller system with the state controller with the direct state feedback (a,b) ($k_i = 107$; $k_I(i_a)=0,082$; $k_2(\omega_1)=3,8$; $k_3(\omega_2)=2,2$; $k_4(m_s)=0,17$; $k_5(m_o)=0,05$) as well as with the state observer (c,d) and with the Kalman filter (e,f). As follows from Fig.7, responses of the system to changes of the speed reference value in all analysed systems are almost identical. The

difference occurred when the load torque was changed. The response to the load torque change of the direct state feedback control system contained no oscillations. The system with the Kalman filter responded in a similar way. The response to disturbance torque change for the system with the state observer had oscillations caused by the time delay in variable estimation. However, these oscillations were quite quickly suppressed.

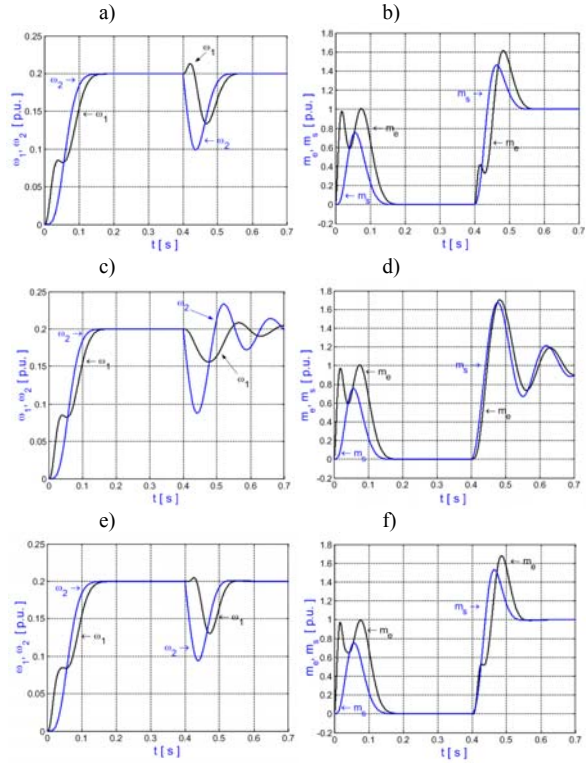


Fig. 7. Transients of the state variable of the system with state controller and: direct state feedback (a,b), state observer (c,d) and Kalman filter (e,f)

V. RESULTS OF EXPERIMENTAL TESTS

A. The experimental set-up

The experimental set-up, presented in Fig.8, was composed of a DC motor driven by a four-quadrant chopper and a DC loading machine.

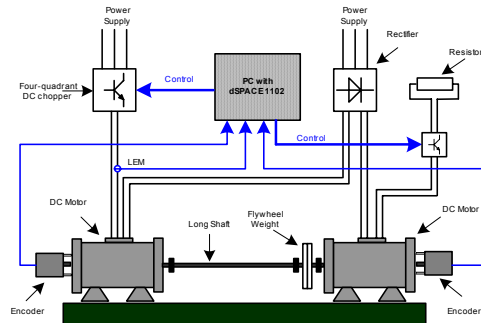


Fig.8. The schematic diagram of experimental set-up

The motor was coupled to a load machine by an elastic shaft (a steel shaft of 5mm diameter and 600mm length). The moment of inertia can be varied

by a flywheel, where the inertia ratio of the motor to the load machine varies from 0.125 to 8. Both motors had the nominal power of 500W each. Speed and position of the drive system were measured by incremental encoders (5000 pulses per rotation). The mechanical system had a natural frequency approximately 9.5 Hz. The control and estimation algorithms were implemented using a digital signal processor with dSPACE software

B. Open loop system

Both estimators of mechanical state variables were tested in the open-loop system, and the measured motor variables were compared to the estimated ones.

First, the system with the Luenberger observer was tested. A lot of experiments were carried out to check the system's performance. The most interesting are transients obtained with changed inertia of the load side. They are presented in Fig. 9, for low speed range.

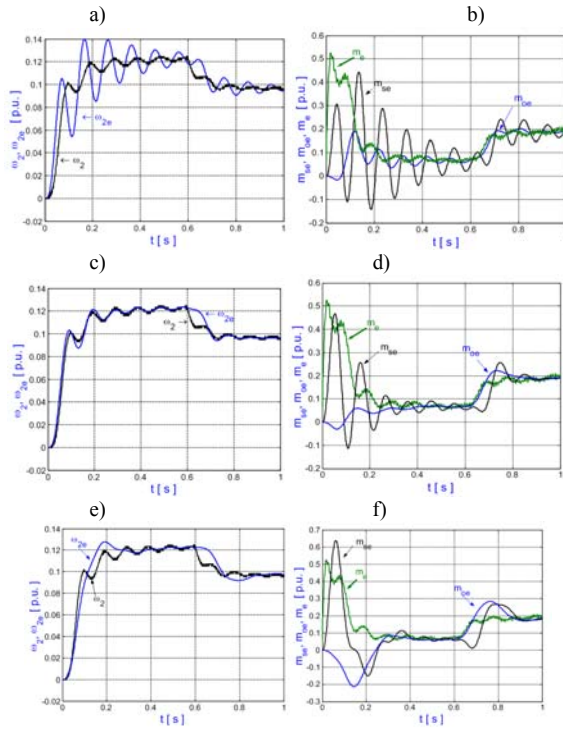


Fig 9. Transients of the real and estimated load speed (a, c, e), motor torque, estimated torsional and load torques (b, d, f), for changed load inertia: 50% (a, b), 100% (c, d), and 200% (e, f) of nominal value using Luenberger observer

In Fig. 9a,c,e transients of real and the estimated motor speed are presented. For smaller value of load side inertia the results are poor. The estimated speed oscillates especially for change of the speed reference value. For nominal parameters of the system (Fig. 9c) the Luenberger observer works very well, only small errors occur while changing disturbance torque. In Fig. 9b,d,f, the motor electromagnetic torque, estimated torsional and disturbances torques are shown. Unfortunately, in the experimental set-up there

is no measurement of these last two variables, so there is no possibility to check the accuracy of estimation.

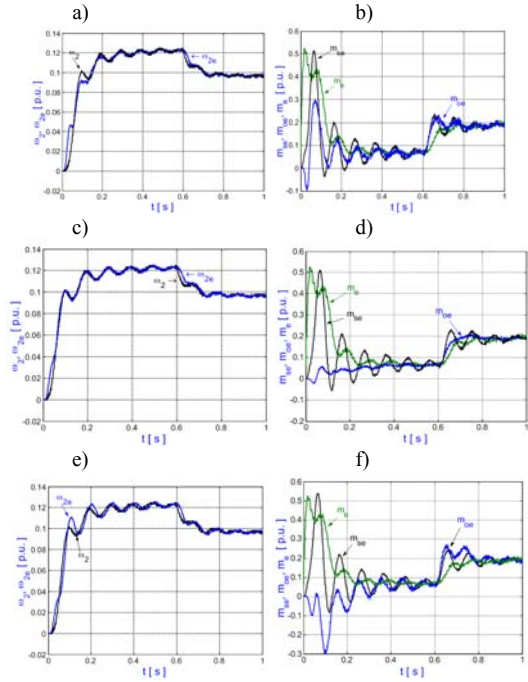


Fig 10. Transients of real and estimated load speed (a, c, e), motor torque, estimated torsional and load torques (b, d, f), for changed load inertia: 50% (a, b), 100% (c, d), and 200% (e, f) of nominal value using Kalman filter

In Fig 10 experimental results obtaining for Kalman filter are presented. The real and estimated load speed transients are presented in Fig. 10a,c,e. Despite of changing parameters of the system, results of the estimation are good. In Fig. 10b,d,f the motor electromagnetic torque, estimated torsional and load torques are presented. In the case of Kalman Filter much smaller estimation errors are obtained in comparison with results for Luenberger observer.

C. Closed loop system

In Fig 11 the transients in PI control structure with additional feedback from torsional torque (a,b) and derivative of torsional torque (c,d) are presented. In both cases the simple estimator (2) provides the information about torsional torque. In both structures the oscillations of torsional torque were effectively damped. The response of the speed control structure with additional feedback from torsional torque (a,b) is faster of than of the second one (c,d).

Next the state feedback control structure was tested. As resulted from previous simulation and experimental tests, for nominal parameters of the system the performances of the Luenberger observer were quite good. This method is very often used in practice as the computation algorithms are not complicated in comparison to the Kalman filter. For this reasons the state feedback control with the Luenberger observer was used in the real drive system.

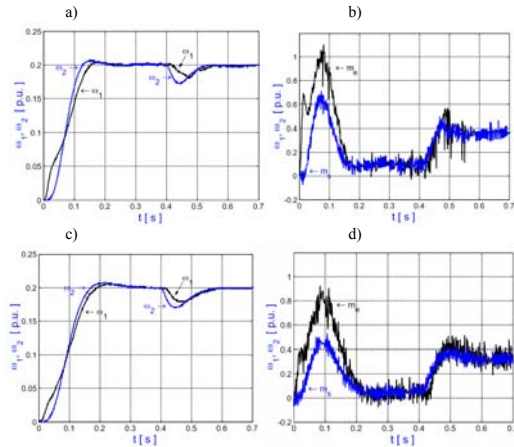


Fig. 11. Transients of the classical PI system with additional feedback from torsional torque (a,b) and derivative of torsional torque (c,d)

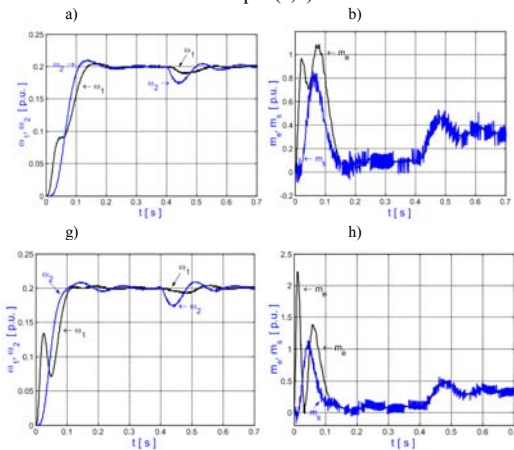


Fig. 12. Transients of the system with direct state feedback (a,b,e,f) and state feedback with the observer (c,d,g,h)

In Fig. 12 the transients of state feedback structure with Luenberger observer are presented. The closed-loop poles of the system with transients shown in Fig. 12 were chosen as follows: $\mu_{1,3} = -46 + i46$, $\mu_{2,4} = -46 - i46$, $\mu_5 = -46$ (Fig. 12a,b) and $\mu_{1,3} = -64 + i64$, $\mu_{2,4} = -64 - i64$, $\mu_5 = -64$ (Fig. 12c,d). Shifting poles of the closed-loop system to the left, made the difference between analysed systems clearly visible. When the speed reference value and/or the disturbance torque were changed, the system with the observer responded with small oscillations. Transients of systems varied due to the time delay of variables estimation, measurement noises, and imprecise identification of the drive system. Nevertheless, the application of the state controller cooperating with the Luenberger observer allowed effective suppressing of the occurring oscillations and optimisation of the system speed response dynamics.

VI. CONCLUSION

In the paper results of simulation and experimental tests for the two-mass system were presented. Two control structures, i.e. classical PI speed control

structure with additional feedbacks and the structure with the state controller were used in order to suppress the system oscillations effectively.

The classical PI structure with one additional feedback can be used in the case when the main requirement is suppression of torsional vibrations and the speed of the responses is not so important. This structure can ensure very effective damping. The main advantage of the structure is its simplicity. It could successfully work in many applications.

The state feedback control structure can be used in the case when effective damping of torsional vibrations and fast responses of the system are required simultaneously. This structure needs the information about all state variables of the system. As in the real systems measurements of certain variables are troublesome, two methods of state variables estimation can be used: the Kalman filter and the Luenberger observer. The quality of estimation of the two methods in an open-loop system was compared and the correctness of their operation in a closed-loop system was examined. As the Luenberger observer requires less computational effort, the observer was selected to real system application. The real system cooperating with this observer provides effective dumping of occurring oscillations. The dynamics of the system depends on the poles placement of the closed-loop system and it can be formed to a large extent.

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