Time optimal control of positioning system of mass storage device with two winding VCM

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Abstract

In this article mathematical model of double windings VCM motor used in hard disk drives and time optimal control algorithm is presented. The mathematical model of VCM motor is given by set of ordinary differential equations. The mathematical model of time optimal control of VCM motor was implemented in Matlab/Simulink and on dSpace DS1104 digital signal processor card. Results of simulation and its comparisons with measurements are presented.

1 Introduction

In recent years there has been a significant increase in hard drive capacity, this leads to an increase of data areal density, which reaching in the laboratory values of 2 Tb/in^2 or more [1], [2]. Such a high areal density places high demands on positioning systems for reading and writing heads. The positioning system must characterized by high angular acceleration, high precision and ability to eliminate vibration taken from the drive platters. In order to fulfill these requirements the VCM (Voice Coil Motor) motor, which is the main source of driving torque of the head arm, in modern hard disks he is supported by auxiliary motors (piezoelectric or electrostatic) [3-6]. The very interesting properties have VCM motor with two armature windings. The first main winding ensures the high angular acceleration in the search phase and the second auxiliary allows for precision tracing of data track in tracking phase. In addition, it would serve to angular speed measurements, and may be used for elimination the vibration generated by rotating drive platters. In this article prototype system for positioning heads equipped with VCM motor with two windings is presented. As a control algorithm of VCM motor the time optimal control algorithm is used.

2 Physical and mathematical model of two armature VCM motor

The general view of two armature VCM motor is in Fig.1 presented (for better presentation the motor geometry was spread). The conceptual model consist of two armature windings ① and ②, situated one above another. The rest of head positioning system components depicted in Fig.1. are as follows: coil holder ③, base for bearing mounting ④, single E-block arm ⑤ and distance ⑥, stator ⑦ with permanent magnet ⑧.

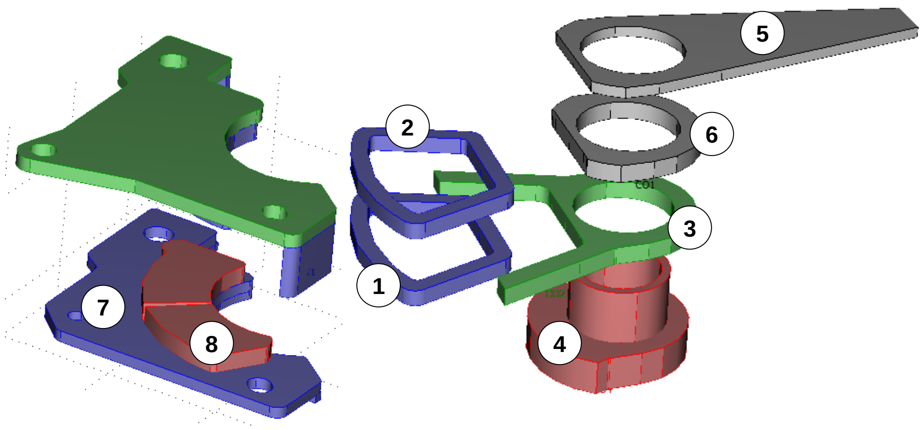

Figure 1. Geometry of two armature VCM motor and the rest of head positioning system components

For such construction of VCM motor, positioning system can be represented by the equivalent scheme presented in Fig. 2, which is composed of two electrical circuits RLE electromagnetically coupled with each other, and the mechanical system composed of the mass moment of inertia J_b with only one degrees of freedom. The mechanical system representing (in the simplest possible case) the system inertial masses (the sum of inertial mass of the E-block, armature winding, slides suspensions, slides and heads) and the elastic element (representing the stiffness of the flexible printed circuit, including voltage supply inlet the armature circuit) [7].

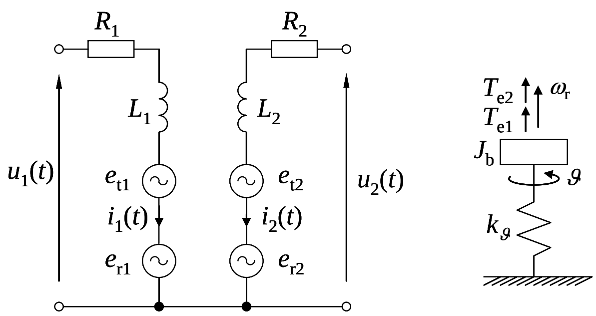

Figure 2. Circuit representation of two armature VCM motor [7]

In Fig.2: R_1, R_2 and L_1, L_2 denotes respectively resistances and self inductances of windings, e_{t1}, e_{t2} and e_{r1}, e_{r2} denotes induced (transformed) voltages and back electromotive force voltages, $u_1(t)$, $u_2(t)$ and $i_1(t)$, $i_2(t)$ power supply voltages and windings currents, T_{e1}, T_{e2} – electromagnetic torque generated separately by two armatures, ϑ, ω_r – angular displacement and angular speed of the rotor, k_ϑ, J_b – stiffness of flexible printed circuit and mass moment of inertia (of all mechanical components of positioning system). For circuit presented in Fig.2 the following equation can be written:

$$\begin{cases} \dfrac{d}{dt}\begin{bmatrix} i_1(t) \\ i_2(t) \end{bmatrix} = \begin{bmatrix} L_1 & L_m \\ L_m & L_2 \end{bmatrix}^{-1} \left(\begin{bmatrix} u_1(t) \\ u_2(t) \end{bmatrix} - \begin{bmatrix} R_1 & 0 \\ 0 & R_2 \end{bmatrix} \begin{bmatrix} i_1(t) \\ i_2(t) \end{bmatrix} - \begin{bmatrix} e_{r1} \\ e_{r2} \end{bmatrix} \right) \\ \dfrac{d\omega_r}{dt} = \dfrac{1}{J_b}(T_{e1} + T_{e2} - k_\vartheta \vartheta - b\omega_r) \\ \dfrac{d\vartheta}{dt} = \omega_r \end{cases} \tag{1}$$

where L_m – mutual inductances between armature coils, b – mechanical dumping, t – time.
The equations for back electromotive force voltages constant $k_{e1,2}$ and torque constant $k_{t1,2}$ can be expressed by:

$$k_{e1,2} = k_{t1,2} = 2N_{1,2}B(2r_1 l + l^2) \tag{2}$$

where $N_{1,2}$ – number of turns of armature coils, B – average value of magnetic flux density in air gap, r_1 – coils rotations radius, l – length of one side of coil in magnetic field.
Expirations for torque components and back electromotive force voltage for single armature coil are as follows:

$$T_{e1} = 2N_1 B(2r_1 l + l^2) i_1(t) \tag{3}$$

$$e_{r1} = 2N_1 B(2r_1 l + l^2)\omega_r \tag{4}$$

3 Structure of the time optimal control of VCM motor

The general solution for control signal (armature current) of time optimal control of VCM motor, may be find in [8], and it is as follow:

$$\hat{i} = i_{\max} \operatorname{sgn}\left(\sqrt{2\frac{k_t i_{\max}}{J_b}\left(\vartheta - \vartheta_0\right)} - \omega_z \right) \tag{5}$$

where ω_z – angular velocity of the motor, $i_{\max}$ – maximum allowable current values, ϑ_0 – initial angular position, $\hat{i}$ – armature current under time optimal control.

Implemented schema of control (realizing the Eqn.5) in Matlab/Simulink environment is show in Fig. 3.

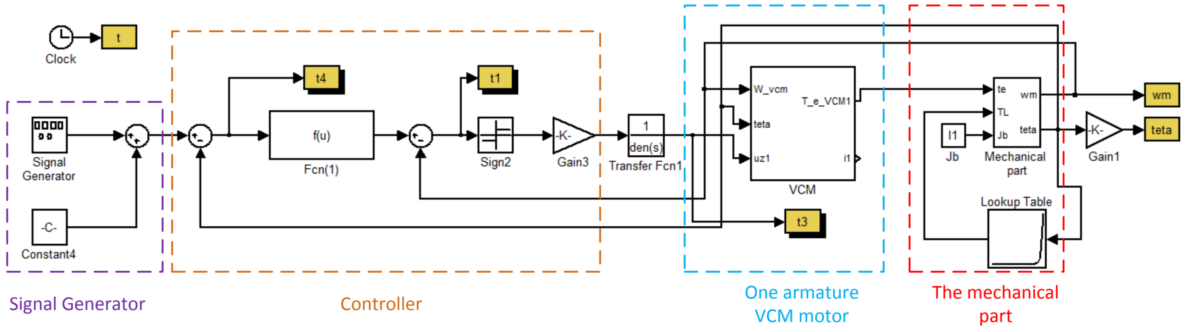

Figure 3. Implementation of time optimal control of exemplary single armature VCM motor

The implementation of time optimal control algorithm and VCM motor model which is presented in Fig.3 can be divided into 5 blocks. The first one, "Signal Generator" is used to inflict the head arm angular displacements in range from 5 to 31 degrees, with frequency of 1 Hz. The second block, "Controller" implements control algorithm according to Eqn.5. The third block, "Transfer Fcn1" is the transmittance of the power amplifier. The last two blocks are one armature VCM motor with a mechanical system.

The software implementation of the time optimal control is in Fig.5 presented, and it operates with a laboratory test bench presented in Fig. 4. The laboratory test bench consist of dSpace 1104 signal processors card (implementation of time optimal controller), is also equipped with a Keyence LK-G152 laser displacement meter for indirect measurements of E-block angular displacement, power amplifier, PC and prototype of VCM motor.

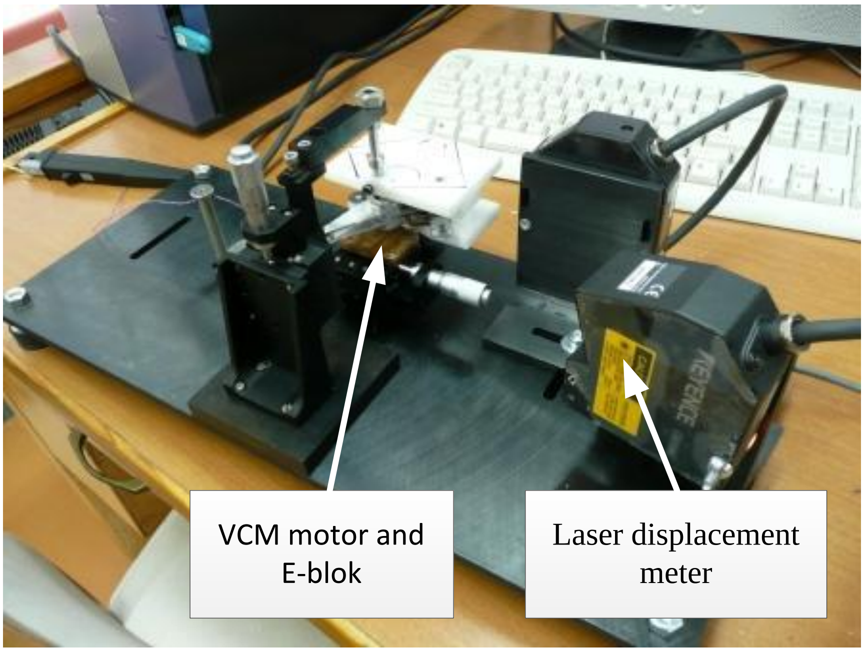

Figure 4. Test bench for investigations of VCM motor time optimal control

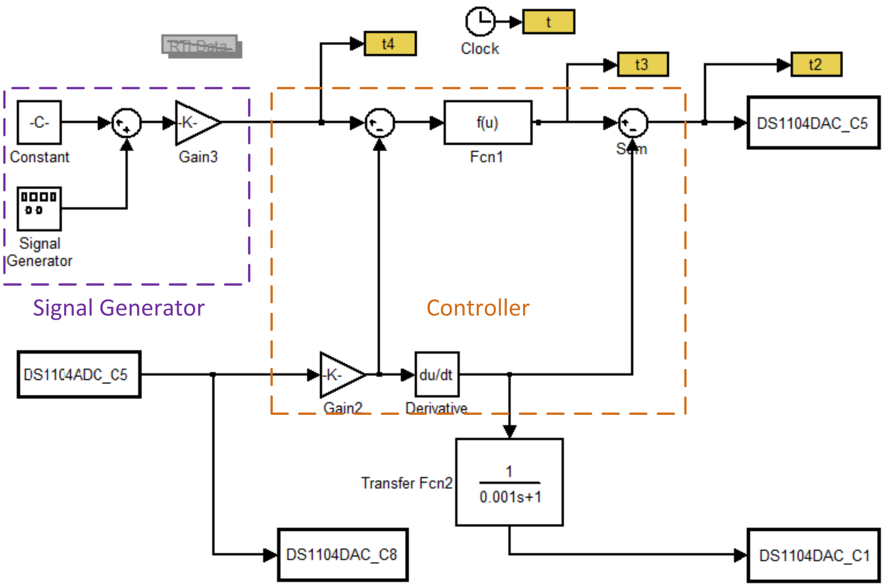

Figure 5. The controller of time optimal control implemented on the signal processor card dSpace 1104

The implementation of time optimal control presented in figure above includes two fundamental parts, "Controller" and "Signal Generator" which performs the same tasks as in the case of “Implementation of time optimal control” shown in Fig. 3. The DSC1104_ADC_C5 block is used to measure angular displacement using a laser sensor. The last two blocks are outputs of dSpace cards. They are connected to an external oscilloscope (Tektronix TDS3054) which recording the angular displacement waveforms (DS1104DAC_08) and the angular speeds waveforms (DS1104DAC_C5). Figs 7 and 8 shown the results of measurements and simulations of angular displacement of E-block in the range of 5 to 31 degrees.

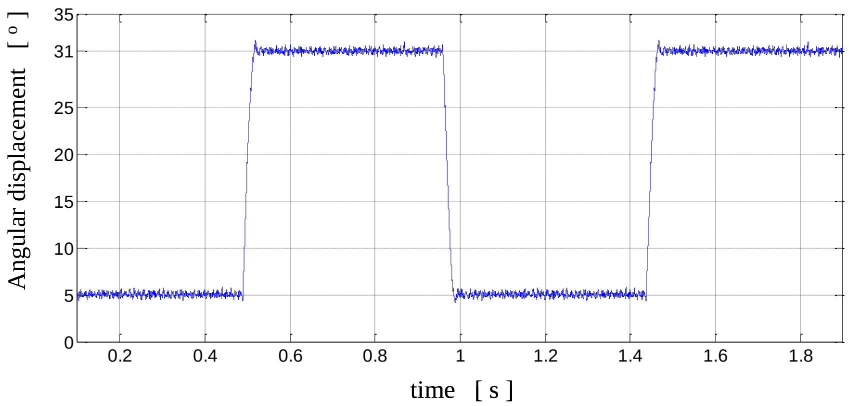

Figure 6. Angular displacement of E-block- the results of the measurements

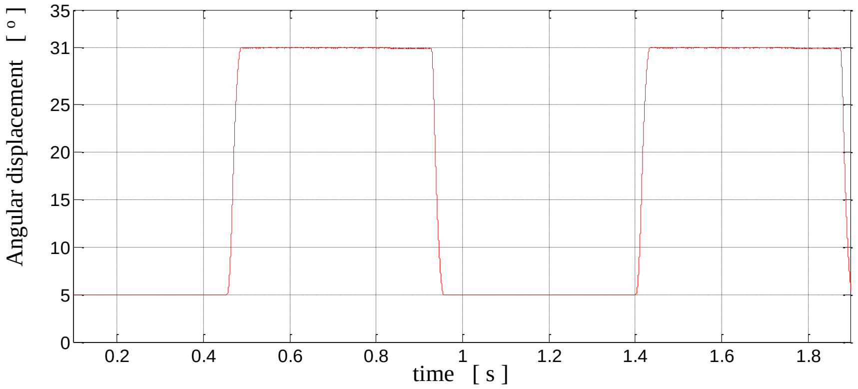

Figure 7. Angular displacement of E-block - the results of the simulation.

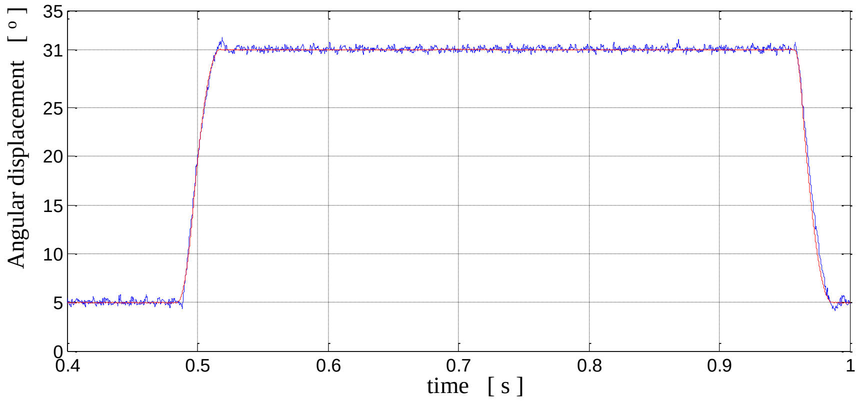

Fig 9. Comparison of the angular displacement the E-block. Blue waveform- results of measurement, the red waveform- result of simulation.

Fig. 9 shows the comparison of angular displacement waveform obtained by simulation and measurements. Both waveforms are characterized by the same positioning time of the E-block, reaching value 31 ms. Additionally, in a registered course "chattering" effect can be seen on Fig. 10, consisting of a fast switching control around a reference angular position. Switching also occurs in the simulations Fig. 11, however it has 20 times smaller amplitude.

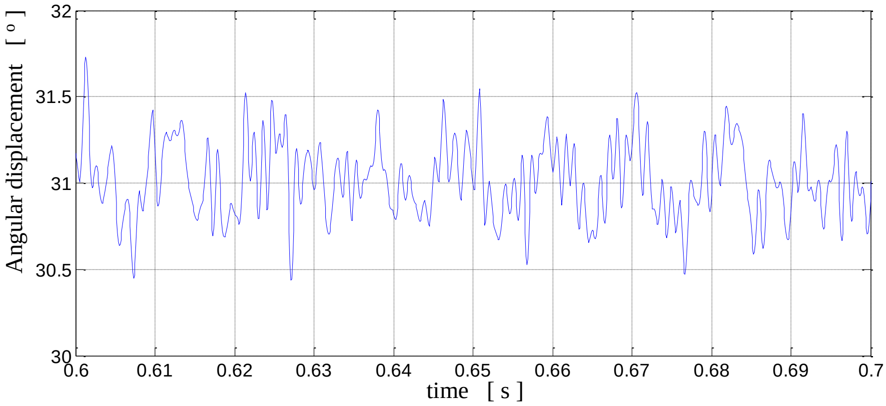

Fig 10. Chattering phenomenon - the results of the measurements.

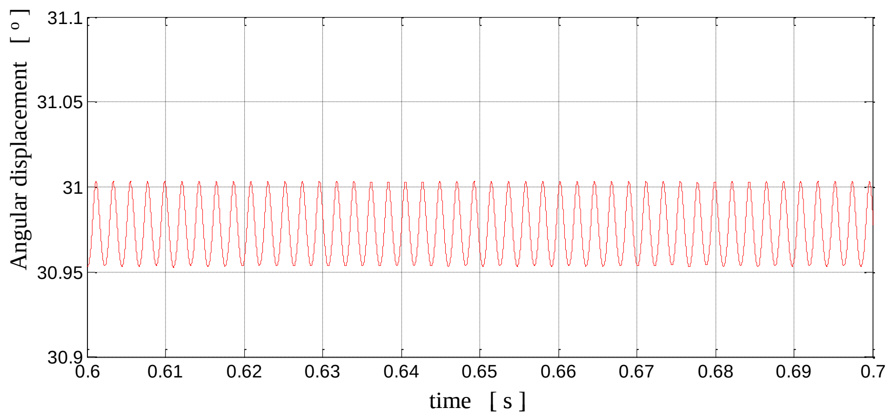

Fig 10. Chattering phenomenon - the results of the simulation

Figs 12 and 13 shows the angular velocity waveforms the E-block taken from measurements and simulations. The characteristic triangles representing angular speed during acceleration (rising edge) and decelerations (falling edge) of E-block and VCM motor are typical for time optimal control.

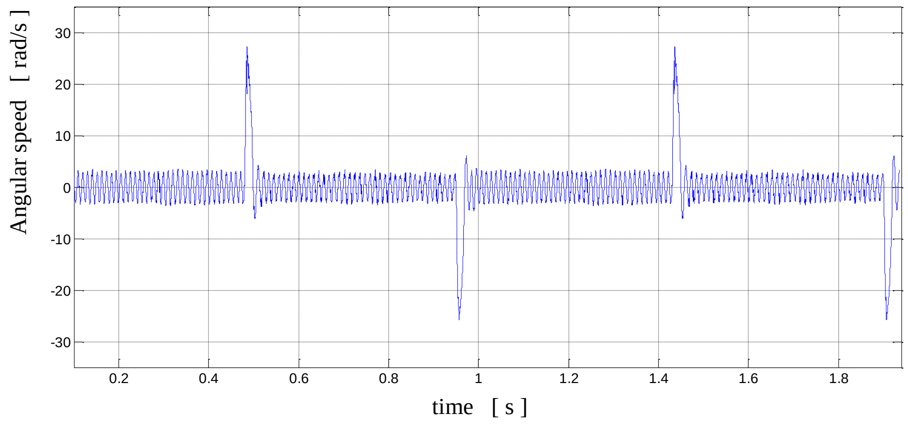

Fig 12. The angular velocity of the E-block - the results of the measurements

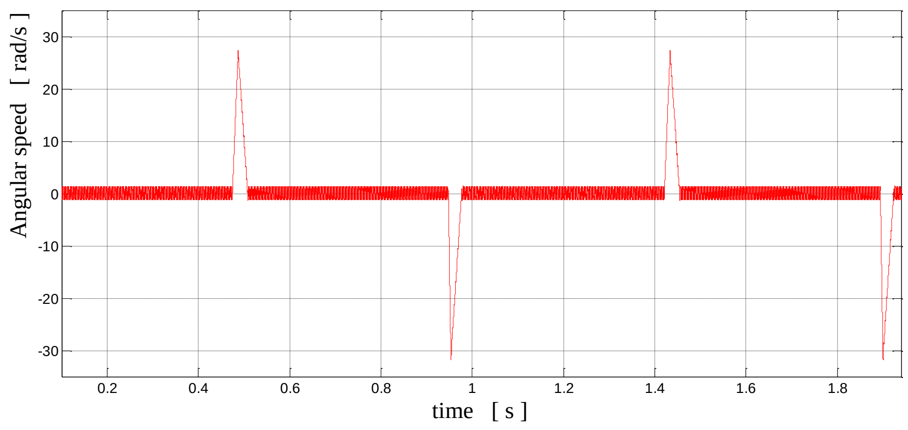

Fig 13. The angular velocity of the E-block - the results of simulation

4 Structure of time optimal control of two armature VCM motor

The time optimal control of VCM motor with two armature is show in Fig. 14. It includes the same: control block “Controller”, signal block “Signal Generator” and a block representing the mechanical part as in the case of control shown in Fig. 4.

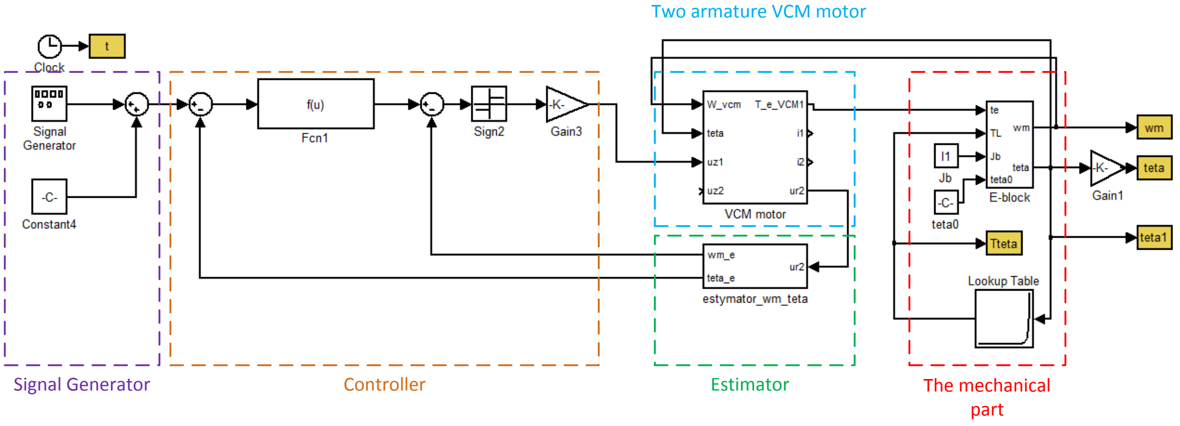

Fig 14. Implementation of time optimal control of two armature VCM motor

The VCM motor has a second coil, which is short circuited by resistor. The voltage drop on short circuiting resistor (omitting influence of voltage drop on second armature inductances an internal resistance) is proportional to induced voltage resulting from motor motion. Basing on this measured voltage it is possible to calculated the real value of angular speed and position of the E-block. It can be done by following formula:

$$\omega_{re} \approx \frac{-u_{r2}}{2N_2B(2r_1l + l^2)} \tag{6}$$

$$\vartheta = \int \omega_{re}\mathrm{d}t + \vartheta_0 \tag{7}$$

An exemplary comparison of simulations results representing angular displacement of E-block driven by single and two armature VCM motor are shown in Fig.15.

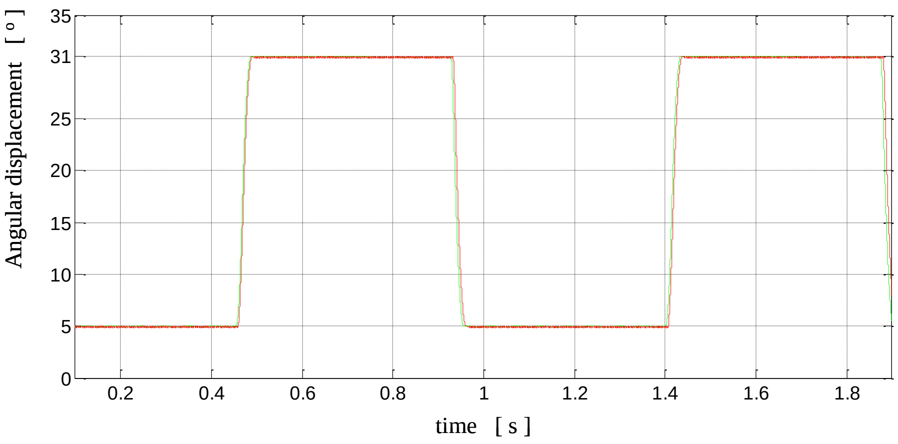

Fig 15. Angular displacement - the results of simulation two armature VCM motor (red curve), and one armature VCM motor (green curve)

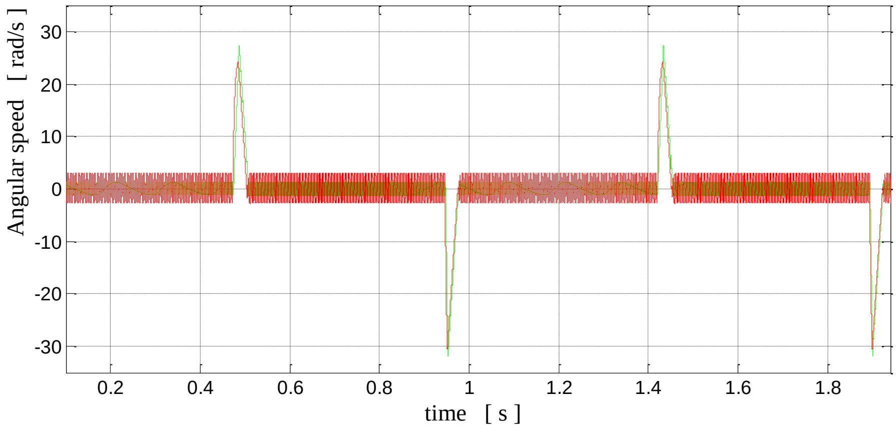

Fig 16. The angular velocity of the E-block - the results of simulation two armature VCM motor (red curve), and one armature VCM motor (green curve).

In Fig.16 the comparison between angular speed of single and two armature VCM motor is shown. The values obtained in both simulations are similar.

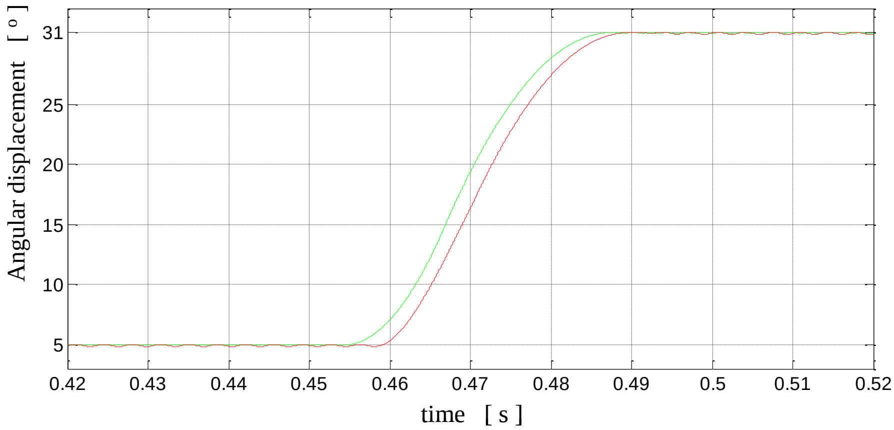

Fig 17. Angular displacement - the results of simulation of two armature VCM motor (red curve), and one armature VCM motor (green curve).

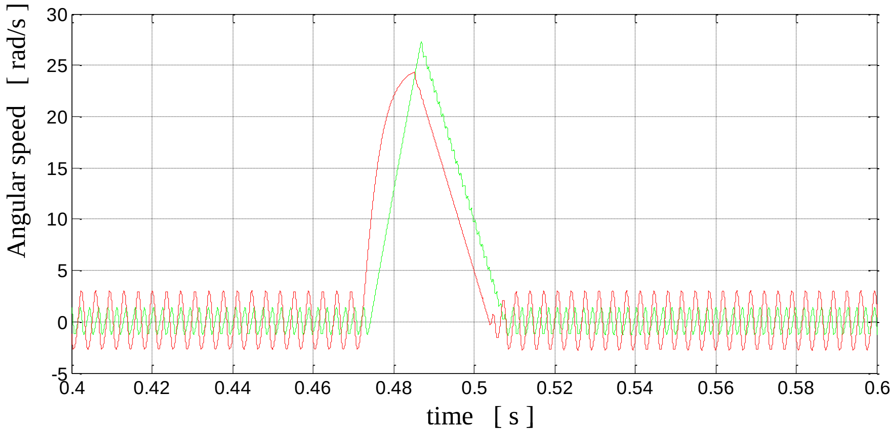

Fig 18. The angular velocity of the E-block - the results of simulation of two armature VCM motor (red curve), and one armature VCM motor (green curve)

In Figs. 17, 18 shows enlarged waveforms of Figs. 15, 16. Both engines shifted E-block in the range from 5 to 31 degrees, but motor with two armature has bigger vibrations around a desired position, also reach a smaller angular velocity.

5 Conclusions

In this article was presented mathematical model of two armature VCM motor controlled by the time optimal control algorithm. In first case the VCM motor mathematical model with single armature has been implemented in Matlab / Simulink, and then verified by comparison with measurements performed on a real object. The results of simulations and measurements agreed, what confirms the correctness of the mathematical model of a VCM with one armature. In simulation of two armature VCM motor angular velocity and angular displacement was calculated on the basis of the voltage inducted in second coil. Simulation waveforms of displacement and angular velocity waveforms agree with a waveforms of one armature motor. It has been shown in this way that the angular velocity and displacement can be estimated basing on the induced voltage without the use of a laser displacement meter.

Literature

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