ДОДАТОК А

Фрагмент коду програми

```
clear;clc;
loadXcosLibs(); loadScicos(); exec('FormatCharts.sce',-1)
function res=simulation(Ue, dt);
   importXcosDiagram("comp1.zcos");
   typeof(scs_m);
   scs_m.props.context;
   Context.Ue=Ue; Context.dt=dt;
   scicos_simulate(scs_m,Context);
   res=[x1,x2,x3,x4,UE];
endfunction
function res=identification(t, w, I, u)
   n=round(length(t)); dt=t(2)-t(1);
   a11=sum(I(2:n).^2); a12=sum(I(1:n-1).*I(2:n)); a13=sum(w(1:n-1).*I(2:n));
   a22=sum(I(1:n-1).^2); a23=sum(w(1:n-1).*I(1:n-1)); a33=sum(w(1:n-1).^2);
   b1=dt*sum(u(1:n-1).*I(2:n)); b2=dt*sum(u(1:n-1).*I(1:n-1));
   b3=dt*sum(u(1:n-1).*w(1:n-1));
   A=[a11,a12,a13;a12,a22,a23;a13,a23,a33]; b=[b1;b2;b3];
   x=A\b; Le=x(1); Re=(x(1)+x(2))/dt; Be=x(3)/dt;
   res=[Le,Re,Be];
endfunction
actual=[2.3E-3,1.8,2.5];
disp(actual);
res=simulation(170,0.01);
t=res(1).time; w=res(3).values; I=res(4).values; u=res(5).values;
res1=identification(t,w,I,u)
disp(res1); res1=abs(res1-actual)./actual*100;
```

```
disp(res1);
res=simulation(170,0.001);
t=res(1).time; w=res(3).values; I=res(4).values; u=res(5).values;
res2=identification(t,w,I,u)
disp(res2); res2=abs(res2-actual)./actual*100;
disp(res2);
res=simulation(170,0.0001);
t=res(1).time; w=res(3).values; I=res(4).values; u=res(5).values;
res3=identification(t,w,I,u)
disp(res3); res3=abs(res3-actual)./actual*100;
disp(res3);
dt=[0.01,0.001,0.0001]; titlex="$\Delta t$";
DLe=[res1(1),res2(1),res3(1)]; titley="$\varepsilon_L,\%$";
show_window(1); plot(dt,DLe,"ko-","linewidth",2);
FormatCharts(titlex,titley,"",[],1); xsave("comp2_res1.scg");
DRe=[res1(2),res2(2),res3(2)]; titley="$\varepsilon_R,\%$";
show_window(2); plot(dt,DRe,"ko-","linewidth",2);
FormatCharts(titlex,titley,"",[],1); xsave("comp2_res2.scg");
DBe=[res1(3),res2(3),res3(3)]; titley="$\varepsilon_B,\%$";
show_window(3); plot(dt,DRe,"ko-","linewidth",2);
FormatCharts(titlex,titley,"",[],1); xsave("comp2_res3.scg");
```

ДОДАТОК Б

Публікація до кваліфікаційної роботи

Міністерство освіти і науки України

Харківський національний університет радіоелектроніки

Кафедра комп'ютерно-інтегрованих технологій, автоматизації та робототехніки

VII Міжнародна Конференція
ВИРОБНИЦТВО
&
МЕХАТРОННІ СИСТЕМИ 2023

VII International Conference
MANUFACTURING
&
MECHATRONIC SYSTEMS 2023

M&MS
2023
VII International Conference
19-20 October
Kharkiv

M&MS 2023, 19-20 October, Kharkiv, UKRAINE

Technical State Estimation for Electromechanical Wheeled Platforms with Parametric Identification Using

Oleksandr Narozhnyi[1], Yurii Romashov[2]
1. CITAR department, Kharkiv National University of Radio Electronics, UKRAINE, Kharkiv, Nauky Ave. 14, email: oleksandr.narozhnyi@nure.ua
2. CITAR department, Kharkiv National University of Radio Electronics, UKRAINE, Kharkiv, Nauky Ave. 14, email: yurii.romashov@nure.ua

Abstract: The approach based on parametric identification to estimate the technical state of electromechanical wheeled platforms is discussed in this research. It is shown, that parametric identification allows having the continuous estimations about the current technical state of an electromechanical wheeled platform during the operation without necessities of the separate especial technical controlling procedures. Implementation of such parametric identification will allow optimizing the time schedule for technical maintenance of electromechanical wheeled platforms.
Keywords**:** identification, wheeled platform, electric motor.

I. Introduction

Development of the suitable time schedule for technical maintenance is the important for effective exploitation of electromechanical wheeled platforms widely used for different purposes at present [1-3]. It is more suitable to provide the continuous estimation of the technical state for electromechanical wheeled platforms during exploitation, because of the such way gives the fully data required to have the most optimal time schedule for technical maintenance.

One approach providing the continuous estimation of the technical state for the wheeled platforms can be based on improved measuring based on the complicated mathematical models in coupling with the identification procedures, like it was discussed in the research [4] for example. To use mathematical models and identification to have the estimations about the technical state of the electromechanical wheeled platforms requires developing some specifics of identification results transformation to technical state estimations, and this research will be about it. Thus, the purpose of this research is in developing the approaches based on mathematical modelling and identification procedures for technical state estimation of electromechanical wheeled platforms.

II. Generalized theory

We will consider further, that the technical state of an electromechanical wheeled platform can be characterized by the finite set of some numerical parameters. Changes in the technical state of the researched electromechanical wheeled platform during the exploitation can be imagined so that the numerical parameters defining the technical state are the functions of the time. Thus, the technical state of the researched electromechanical wheeled platform can be defined during the exploitation through the set time depended functions:

$$\alpha_k = \alpha_k(t),\ k = 1,2,\ldots,N_\alpha, \quad (1)$$

where α_k and N_α are one of the parameters defining the technical state of the wheeled platform and count of such parameters; t and $\alpha_k(t)$ are the time and the function defining the time dependance of the α_k parameter.

Considering the senses of each the parameters (1), we can define the permissible technical states providing the normal exploitation modes of the researched electromechanical wheeled platform by means the following inequations:

$$\alpha_k^{\min} \le \alpha_k \le \alpha_k^{\max},\ k = 1,2,\ldots,N_\alpha, \quad (2)$$

where $\alpha_k^{\min}$ and $\alpha_k^{\max}$ are the parameter α_k boundary values limiting the permissible technical states providing the normal exploitation modes of the researched electromechanical wheeled platform.

Estimation of the technical state of some electromechanical wheeled platform in the form (1), (2) gives the fully data allow optimizing of the time schedule, the costs and others conditions for the technical maintenance. Thus, estimation of technical state of the wheeled platforms will be directed to be found to have it in the view (1), (2).

It is naturally, that the theoretical estimations (1), (2) of the technical state must be based on the mathematical modelling of the researched electromechanical wheeled platforms. To have the mathematical model of some electromechanical wheeled platform, it is necessary to introduce the control parameters and the state parameters characterizing this researched wheeled platform and to consider all these introduced parameters as the functions of the time:

$$\mathbf{u} = \mathbf{u}(t),\ \mathbf{x} = \mathbf{x}(t), \quad (3)$$

where $\mathbf{u}$ is the vector involving the control parameters, but $\mathbf{x}$ is the vector involving the state parameters of the researched electromechanical wheeled platform.

The mathematical model of the electromechanical wheeled platform characterized be the control and state parameters (3) can be generally represented in the form of the system of the ordinary differential equations with the correspondent initial conditions:

$$\frac{d\mathbf{x}}{dt} = \mathbf{f}\left(t, \mathbf{x}; \mathbf{u}(t); a_1, a_2, \ldots, a_{N_a}\right),\ \mathbf{x}(t_0) = \mathbf{x}_0, \quad (4)$$

where $\mathbf{f}(\ldots)$ is the given function defining the velocities of the state parameters for the researched electromechanical wheeled platform; $a_1, a_2, \ldots, a_{N_a}$ and N_a are the parameters of the mathematical model and the count of such parameters; t_0 and $\mathbf{x}_0$ ate the time and the state parameters given for the initial time moment.

Mathematical model (4) allows simulating the state of the researched electromechanical wheeled platform for the given control, the given initial values and the given parameters, so that such simulating can be imagined as the following mapping:

$$\mathbf{u}(t); a_1, a_2, \dots, a_{N_a}; t_0, \mathbf{x}_0 \xrightarrow{t} \mathbf{x}(t). (5)$$

We have a lot of approaches to realize the mapping (5) to have the imitations of the researched electromechanical wheeled platform, but the most general approaches are based on well-known numerical solving of the initial-value problem (4) by means the different computer technologies with specialized scientific software, like in research [4] for example.

It is understandable, that the mathematical model (4) can give au more that computer simulations (5) only, because it is possible to use this mathematical model (4) to estimate the current technical state of the researched electromechanical wheeled platform. The principal idea of technical state estimation of the electromechanical wheeled platform by using the mathematical model is in dependencies between the mathematical model parameters and the parameters of technical state:

$$a_k = a_k\left(\alpha_1, \alpha_2, \dots, \alpha_{N_\alpha}\right),\ k = 1, 2, \dots, N_a, (6)$$

where $a_k\left(\alpha_1, \alpha_2, \dots, \alpha_{N_\alpha}\right)$ are some known functions.

The view of relations (6) is predefined by the building of the researched electromechanical wheeled platform, by the simplifications leading to the mathematical model (4) as well as by the chose technical state parameters (1). Due to the relations (6) we can see that changing the technical state (1) will lead to changing of the parameters of the mathematical model of the researched electromechanical wheeled platform, so we will have the mathematical model (4) parameters as the functions of the time:

$$a_k = a_k(t),\ k = 1, 2, \dots, N_a, \quad (7)$$

where $a_k(t)$ is some function defining the time dependence of the a_k parameter due to time changing of the technical state.

Let, we have the information about some control $\mathbf{u}(t)$ and the state $\mathbf{x}(t)$ corresponded to this control under the known values t_0 and $\mathbf{x}_0$ defining the initial conditions of the researched electromechanical wheeled platform. In this case it is possible to consider the parametric identification, which can be imagined as the following mapping:

$$\mathbf{u}(t); \mathbf{x}(t); t_0, \mathbf{x}_0 \xrightarrow{M_{PI}} a_1(t), a_2(t), \dots, a_{N_a}(t), (8)$$

where M_{PI} is some suitable method for the parametric identification.

It is understandable, that the parametric identification (8) will allow us to have estimations for time changing (7) of the mathematical model parameters. Thus, due to the results of parametric identification (8) and both due to the known relations (6) we will have the representation of the technical state parameters (1) in the following implicit view:

$$a_k(t) = a_k\left(\alpha_1, \alpha_2, \dots, \alpha_{N_\alpha}\right),\ k = 1, 2, \dots, N_a. (9)$$

In the case of $N_a = N_\alpha$ the relations (9) can be considered as the system of the equations, so that the technical state parameters (1) will be represented by solving this system of the equations in each time moment. Of course, that in general case the system of the equations (9) will be nonlinear, and to solve it the correspondent suitable numerical methods must be used, but in some cases the system of the equations (9) can be linear also, and in these cases, it will be easier to estimate the technical state parameters (1), because of linear systems solving is the typical task envisaged in modern computer-aided technologies for scientific and engineering purposes. At the same time, in the more general case of $N_a \neq N_\alpha$ it is impossible to consider the relations (9) as the fully defined system of equations to find the technical state parameters (2), because of we will have the different numbers of the unknowns and of the equations to find them. In this general case of $N_a \neq N_\alpha$, we propose to use the least square method [5] to find the technical state parameters (1) from the relations (9). To do it, we propose to introduce the sum squares of the deviations of the relations [5] in the form:

$$S = \sum_{k=1}^{N_a}\left(a_k\left(\alpha_1, \alpha_2, \dots, \alpha_{N_\alpha}\right) - a_k(t)\right)^2. (10)$$

The squares sum (10) for the given parameters (7) and the relations (6) will be function of the technical state parameters (1) on each time moment:

$$S = S\left(\alpha_1, \alpha_2, \dots, \alpha_{N_\alpha}; t\right), (11)$$

where $S(\dots)$ is some given function.

Due to the square sum of the deviations (11) and the least square method [5] we can have the system of the equations to find the technical state parameters (1) in the following view:

$$\frac{\partial S}{\partial \alpha_i} = 0, i = 1, 2, \dots, N_\alpha. (12)$$

It seems that, the system of the equations (12) must be nonlinear, but we have a lot of possibilities to introduce the technical state parameters (1), and it is suitable to choose such parameters (1) so that, to have the system (12) linear, because it will simplify solving of this system (12). To have the system (12) linear, it is enough to have the relations (6) linear too:

$$a_k = \sum_{j=1}^{N_\alpha} A_{kj}\alpha_j,\ k = 1, 2, \dots, N_a, (13)$$

where A_{kj} are some given numerical parameters.

Let to substitute relations (13) to the generally defined sum squares of the deviations:

$$S = \sum_{k=1}^{N_a}\left(\sum_{j=1}^{N_\alpha} A_{kj}\alpha_j - a_k(t)\right)^2. \quad (14)$$

The system of equations (12) correspondent to the sum of the deviations squares (14) will have the following view:

$$\sum_{k=1}^{N_a}\left(\sum_{j=1}^{N_\alpha} A_{kj}\alpha_j - a_k(t)\right)A_{ki} = 0,\ i = 1, 2, \dots, N_\alpha. (15)$$

To transform the linear equations system (15) to the more suitable view, it will be reasonable to introduce the following values:

$$A_{ij} = \sum_{k=1}^{N_a} A_{ki} A_{kj},\ \beta_i(t) = \sum_{k=1}^{N_a} A_{ki} a_k(t), \quad (16)$$

where $i, j = 1, 2, \ldots, N_\alpha$.

The introduced values (16) allow representing the linear system (16):

$$\sum_{j=1}^{N_\alpha} A_{ij}\alpha_j = \beta_i(t),\ i = 1, 2, \ldots, N_\alpha. \quad (17)$$

Due to the linear system (17) we will have the estimations for the technical state parameters (1):

$$\alpha_k(t) = \sum_{j=1}^{N_\alpha} A_{kj}^{-1}\beta_i(t),\ k = 1, 2, \ldots, N_\alpha, \quad (18)$$

where A_{kj}^{-1} are the elements of the matrix inverse to the matrix with the elements A_{ij}.

Although, it is practically not suitable to find the elements A_{kj}^{-1} of the inverse matrix, because more suitable to use the methods for solving the linear systems like the Gauss method or others similar, but relations (18) are suitable from the theoretical point of view to show directly the estimations of the technical state parameters. Thus, the mathematical model (4), the identification method allowing to have the mapping (8), as well as the relations (16), (18) give us the method for technical state continuous estimating (1) of electromechanical wheeled platform on the basis of the measurements about the actually realized controls and the states corresponded to them during the exploitation.

III. Example of application

It is necessary to note, that building of the suitable mathematical model (4), choosing of the suitable parameters (1) to represent the technical state of the researched wheeled platform, developing of the suitable identification method as well as providing of the required measurements are the complicated problems, which must be considered in mutual connection, but not separately, and this consideration will be unique significantly for each of the particular class of the electromechanical wheeled platforms. The typical application of the proposed approach for the technical state estimating of the electromechanical wheeled platforms will be discussed further on an suitable example.

Let consider firstly the general notes about the principal building of the electromechanical wheeled platforms in connection with the representing their technical state and mathematical modelling. The principal point of view on the electromechanical wheeled platforms is in presence of mutually connected, but made separately mechanical and electrical parts. So, the parameters (1) representing the technical state of the electromechanical wheeled platform must provide estimations of the state both for mechanical and both for electrical parts. As the result, the mathematical model (4) must involve the mathematical models both of mechanical and both of electrical parts, and the connections between these parts. Besides, the mathematical model (4) must be in agreement with the possibilities of instrumental measurements of the state of electromechanical wheeled platforms. Taking into account all these circumstances, it is possible to approve, that the rotation angles of the wheels are the most suitable generalized coordinates to represent the mechanical parts of the researched wheeled platform, including because of it is suitable to provide measurements for the angular velocity. The electric charges in the winding of the drive electric motors rotors are the most suitable generalized coordinates to represent the state of electrical parts of the electromechanical wheeled platforms, including because of it is suitable to provide measurements of the electric currents. The electric voltages supplied to the drive electric motors are the most suitable to represent the control of the electromechanical wheeled platforms, including because of it is suitable to measure the electric voltages. Thus, to represent the control and the corresponded state of the electromechanical wheeled platform under the simple schematization we must use at least the following control and state vector:

$$\mathbf{u}(t) = u(t),\ u(t) = U_e(t), \quad (19)$$

$$\mathbf{x}(t) = (x_1(t) \quad x_2(t))^T,\ x_1(t) = \omega(t),\ x_2(t) = I(t), \quad (20)$$

where $U_e(t)$ is the electric voltage supplied to the drive electric motors; $\omega(t)$ is the angular velocity of the wheels of the researched platform, and $I(t)$ is the electric current in the rotor winding of the drive electric motors.

The mathematical model corresponding to the simplest schematization of the electromechanical wheeled platform with the control (19) and with the state parameters (20) can be built by means the electromechanical analogies and the Lagrange's equations of 2-nd kind and can be represented in the particular view:

$$\begin{cases} \dfrac{dx_1}{dt} = \dfrac{B_e}{J}x_2 - \dfrac{b}{J}x_1^2 - \dfrac{mg\delta}{J}, \\ \dfrac{dx_2}{dt} = -\dfrac{R_e}{L_e}x_2 - \dfrac{B_e}{L_e}x_1 + \dfrac{u(t)}{L_e}, \end{cases} \quad (20)$$

$$x_1(t_0) = \omega_0,\ x_2(t_0) = I_0, \quad (21)$$

where J is the moment of inertia of the electromechanical wheeled platform relatively the rotation axis of the wheel; b is the generalized parameter defining the viscous friction of the electromechanical wheeled platform relatively it rotation axis of the wheel; mg is the total weight value of the electromechanical wheeled platform; δ is the rolling friction coefficient of the wheels; B_e is the electromechanical parameter, but R_e and L_e are the resistance and the inductance of the rotors winding of the drive electric motors; ω_0 and I_0 are the given values of the wheels angular velocity and of the electric current in the winding of the rotor of the drive electric motors art the initial time moment $t = t_0$.

To represent the mathematical model (20) in the view (4), let to introduce the following parameters:

$$a_1 = \frac{B_e}{J}, a_2 = \frac{b}{J}, a_3 = \frac{mg\delta}{J}, a_4 = \frac{R_e}{L_e}, a_5 = \frac{B_e}{L_e}, a_6 = \frac{1}{L_e}. (22$$

The relations (22) correspond to the case of the differential equations (4) with the $N_a = 6$ value. Due to the introduced parameters (22), the differential equations (2) will have the view like in the general representation (4):

$$\frac{dx_1}{dt} = a_1 x_2 - a_2 \frac{b}{J} x_1^2 - a_3, \frac{dx_2}{dt} = -a_4 x_2 - a_5 x_1 + a_6 u(t). (23$$

Thus, in the view (23) we have the simp-lest example of the generalized model (4). Of course, it is possible to have others more complicated than (23) mathematical models allow representing the electromechanical wheeled platforms.

From the differential equations (20), we can see that the technical state of the mechanical parts of the researched electromechanical wheeled platforms is defined by the values of the generalized moment of inertia J, of the generalized parameter b defining the viscous frictions, of the total weight mg as well as of the rolling friction coefficient δ. At the same time, the total weight of the electromechanical wheeled platform can be defined easy by means the simple measurements of the spring's strains for example. Besides, the generalized inertia moment has changes due to changing the total weight, but not the technical state, so we can estimate the generalized inertia moment through the total weight. Thus, we have the principal parameters b and δ representing the technical state of the researched wheeled platforms in agreement with the mathematical model (20), (21). From the differential equations (20), we can see also that the technical state of the electrical parts of the researched electromechanical wheeled platforms is defined by the values of the electromechanical parameter B_e, and of the resistance and the inductance R_e and L_e of the rotors winding of the drive electric motors. At the same time, the resistance of the rotor winding can be measured easy, so the principal parameters B_e and L_e representing the technical state of the researched wheeled platforms in agreement with the mathematical model (20), (21). Thus, for the researched electromechanical wheeled platform represented by the mathematical model (20), (21) it is reasonable to define the parameters (1) of the technical state in the particular view:

$$\alpha_1 = b,\ \alpha_2 = \delta,\ \alpha_3 = B_e,\ \alpha_4 = 1/L_e. \quad (24)$$

The parameters (24) correspond to the particular case of the parameters (1) with the $N_\alpha = 6$ value. By comparing the relations (22) and the relations (24), we can write the following:

$$a_1 = \frac{\alpha_3}{J},\ a_2 = \frac{\alpha_1}{J},\ a_3 = \frac{mg}{J}\alpha_2,$$
$$a_4 = R_e \alpha_4,\ a_5 = \alpha_3 \alpha_4,\ a_6 = \alpha_4. \quad (25)$$

The relations (25) are actually the particular case of the general relations (6). We can see, that not all the relations (25) are linear like the general linear relations (13). At the same time, it is not necessary to use all the relations (25) to have the estimations about the technical state for the electromechanical wheeled platform represented by the simplest mathematical model (20), (21), because of the inequation $N_\alpha < N_a$. Really, it is obviously, that it is not necessary to use the nonlinear relation from (25), because of it is sufficient to use only first three relations (25) with fourth of sixth relation from (25). Thus, the considered example allows to show that the based on the identification proposed generalized approaches for estimation of the technical state of the electromechanical wheeled platforms can be principally used, so that it will be possible to provide continuous estimations of the technical state during the exploitation of the electromechanical wheeled platforms. Of course, that to realize this proposed approach it will be necessary to choose or to develop the suitable identification method to have the mapping (8).

IV. Conclusions

This research presents the noticeable results about developing the approaches based on mathematical modelling and identification procedures for technical state estimation of electromechanical wheeled platforms, so that we can formulate some really principal statements.

Firstly, the mathematical modelling with the identification procedures really give us the effective way to have estimations about the technical state of the electrotechnical wheeled platforms, and these estimations can be continuously during the exploitation. Secondly, the possibilities of the technical state estimations of the electromechanical wheeled platforms are predefined by the simplifications used to formulate their mathematical models. Thirdly, it is wished to have the linear relations between parameters of the mathematical model and the parameters defining the technical state of the researched electromechanical wheeled platform to exclude difficulties in the identification procedure by the least square method. Fourthly, it is necessary to develop the identification procedure for mathematical models of the electromechanical wheeled platforms, which is recommended for the further researches.

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ДОДАТОК В

ДЕМОНСТРАЦІЙНИЙ МАТЕРІАЛ

№	ПОЗНАЧЕННЯ	НАЙМЕНУВАННЯ	Дод. відомості
		Текстові документи	
1	ГЮІК. 627914.020 ПЗ	Пояснювальна записка	79с. ф. А4
		Графічні документи	
2		Демонстраційний матеріал	у форматі
			*.ptt

					ГЮІК. 627914.020 ВД			
Змін.	Арк.	Номер докум.	Підп.	Дата				
Розроб.		Нарожний О.О.			Розроблення методу автоматизованої оцінки поточного технічного стану колісної електромеханічної платформи на основі параметричної ідентифікації Відомість кваліфікаційної роботи	Літера	Арку	А
Перевір.		Ромашов Ю.В.				Н	1	1
						Кафедра КІТАР ХНУРЕ		
Н.контр.		Демська Н.П.						
Затв.		Невлюдов І.Ш.						