Adaptive Control of Vehicle Position with Non-linearizable Feedback

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Abstract – **The problem of vehicle control is considered in the paper. The model of vehicle is represented by the equations of kinematics and dynamics of a rigid body. The features of control that could appear for complicated maneuvers are investigated. In such motion the determinant of the matrix of kinematics may be equal to zero. This fact does not allow to set the desired dynamics of the closed-loop system in the form of linear equations. In other words the system cannot be linearized by feedback. The problem is solved by applying adaptive control systems with a reference model. A procedure for the synthesis of the basic position-trajectory control is proposed. Asymptotic stability analysis on base of the method of Lyapunov functions is considered. Adaptation of control is carried out by proportional and integral algorithms. The block-diagram of the closed-loop system is presented. The stability of the adaptive control system is proved. It is shown that in the linear approximation, the characteristic equation of the closed-loop system is a product of the characteristic equation of the reference models, the vehicle, and the adaptation subsystem. Modeling results are presented.**

Keywords-position-path control, adaptive control, vehicle, reference model, function of Lyapunov.

I. INTRODUCTION

The relevance of the solution of problems of control of vehicles in real time is explained by requirements to operate autonomously. Current trends in the development of theory and systems of vehicles [1] were presented in the XII Russian Conference on Control Problems reflected. Work [2] specifies the following main directions of development of the industry: control of aviation and aerospace vehicles; control of maritime vehicles; mechatronics, control and information processing in robotic systems; navigation of vehicles. Plenary reports indicate the relevance of tasks related to: navigation of vehicles; versatile control of vehicles, functioning in different modes; control of modern spacecraft. Topics of section reports allows conclude about currently relevant problems of high-precision control in maneuvering, the extension of operation through more detailed mathematical models, increasing the autonomy of existing vehicles, extension of control intelligence and coordination of the various levels of systems.

Great attention to the planning and control of vehicles was paid in 19 World Congress IFAC on control, held in August 2014 in Cape Town (South Africa). There were made 3 out of 8 reports on robot control and intelligent systems. More than 25% of the sections of Congress were dedicated to the control of mobile robots, vehicle, planning, navigation, and intelligent control of vehicles. Furthermore, a large number of submitted reports concerns particular issues, reflecting the specific operating environment of vehicles.

Method of position-trajectory control [3], which origin comes from [5-7], has recently been successfully applied in autonomous aeronautic complexes [8-11] and autonomous marine vehicles [12-15]. Position-trajectory synthesiz algorithms were applied for the prototype of high-altitude aeronautical platform, successfully tested in December 2013 in Changsha (China). Prototype of unmanned boat in autonomous motion along specified routes with automatic detection and avoiding obstacles is successfully tested in March 2014 in Taganrog Bay.

The main limitations of the position-trajectory control systems are related to two aspects.

First, the algorithms for position-trajectory control sets the linear model of the closed-loop control system, i.e., the original system is linearized. We denote that similar restrictions for non-linear systems synthesis methods are occurred quite often, because subject fulfillment of certain conditions for a certain models of non-linear processes allows effective synthesis of the control [16]. Particularly when the matrix of kinematics is nonsingular, model of a rigid body is a system, linearized by feedback.

Second, disturbances estimators synthesized unrelatedly to control loop are used for adaptation of the control system in [8 - 15]. This leads to the need to improve the speed performance of the estimator, which in increases the sensitivity of the system to noise.

In this paper, the adaptation is carried out within searchless adaptive systems, originated from Institute of Control Sciences RAS [17-19]. This approach has proven its effectiveness and feasibility and continues to develop [20, 21]. As far as specific tasks of control of vehicles (docking, motion with obstacles) requires high quality control in the dynamics, this paper is based on the ideas of systems with reference model [22-25], which allow to adapt in transient modes.

II. SYNTHESIS OF CONTROL LOOP OF NOMINAL REFERENCE MODEL BUILDING A MODEL

We consider the nominal model of the vehicle of the form [3, 4]

$$\begin{aligned} \dot{y}_m &= R\left(y_m\right) x_m \\ \dot{x}_m &= M^{-1}\left(F_{um} + F_{dm}\right) \end{aligned} \tag{1}$$

Where y_m is the vector of linear and angular positions of a mobile vehicle in the external coordinate system; x_m is the vector of linear and angular velocities of a mobile vehicle in the body coordinate system; $R(y_m)$ is matrix of the nominal kinematics model; F_{um} is the vector of control forces and moments; F_{dm} is the vector of various forces and moments acting on the mobile vehicle.

We synthesize for the nominal model (1) controls for stabilization at a given point. In accordance with the method of position-trajectory control [3] we introduce an error in the form

$$\Psi_{REF} = A_1 y_m + A_2, \quad (2)$$

Where A_1, A_2 are matrix and vector of constant coefficients, reflecting the requirements for point positioning.

Consider the quadratic function of the form

$$V_{REF1} = 0.5\Psi_{REF}^T \Psi_{REF}. \quad (3)$$

The time derivative of (3) regarding equations (1), (2) are equal

$$\dot{V}_{REF1} = \Psi_{REF}^T \dot{\Psi}_{REF} = \left(A_1 y_m + A_2\right)^T A_1 R_m x_m. \quad (4)$$

In order to provide the negative definiteness of the function (4) x_m is given as:

$$x_m = -Q_{REF} R_m^T A_1^T \left(A_1 y_m + A_2\right), \quad (5)$$

Where Q_{REF} is positively definite matrix.

Expression (5) is the desired state of the nominal model (1). On the basis of (5) the error of a closed-loop control system of reference model is formed

$$\Psi_{VREF} = x_m + Q_{REF} R_m^T A_1^T \left(A_1 y_m + A_2\right) \quad (6)$$

The time derivative of the expression (6), taking into account the nominal model (1) is equal to

$$\dot{\Psi}_{VREF} = M^{-1}\left(F_{um} + F_{dm}\right) + Q_{REF} \dot{R}_m^T A_1^T \left(A_1 y_m + A_2\right) + Q_{REF} R_m^T A_1^T A_1 R_m x_m \quad (7)$$

We demand that error (7) comply with the following reference differential equation

$$\dot{\Psi}_{VREF} + T_1 \Psi_{VREF} = 0 \quad (8)$$

Where T_1 is positively defined matrix of the controller settings.

We substitute expressions (6), (7) in equation (8), we obtain an algebraic equation for vector of control of nominal model F_{um}, which solution is

$$F_{um} = -F_{dm} + M \begin{pmatrix} -Q_{REF} \dot{R}_m^T A_1^T \left(A_1 y_m + A_2\right) - \\ -Q_{REF} R_m^T A_1^T A_1 R_m x_m - \\ -T_1 \left(x_m + Q_{REF} R_m^T A_1^T \left(A_1 y_m + A_2\right)\right) \end{pmatrix} \quad (9)$$

Consider the quadratic function

$$V_{REF2} = 0.5\Psi_{VREF}^T \Psi_{VREF} \quad (10)$$

Derivative of the expression (10) along trajectories of the the system is

$$\dot{V}_{REF2} = \Psi_{VREF}^T \dot{\Psi}_{VREF} = \left(x_m + Q_{REF} R_m^T A_1^T \left(A_1 y_m + A_2\right)\right)^T \times \begin{pmatrix} M^{-1}\left(F_{um} + F_{dm}\right) + Q_{REF} \dot{R}_m^T A_1^T \left(A_1 y_m + A_2\right) + \\ +Q_{REF} R_m^T A_1^T A_1 R_m x_m \end{pmatrix} \quad (11)$$

Substituting (9) into (11) we get

$$V_{REF2} = -\left(x_m + Q_{REF} R_m^T A_1^T \left(A_1 y_m + A_2\right)\right)^T \times T_1 \left(x_m + Q_{REF} R_m^T A_1^T \left(A_1 y_m + A_2\right)\right) \quad (12)$$

Because the expression (6) not converts system (1) and (9) into an identity, then according to Barbashin-Krasovskii additions, closed nominal system is asymptotically stable.

The equation of nominal model, closed by control (9) have the form

$$\begin{aligned} \dot{y}_m &= R(y_m) x_m, \\ \dot{x}_m &= -Q_{REF} \dot{R}_m^T A_1^T \left(A_1 y_m + A_2\right) - Q_{REF} R_m^T A_1^T A_1 R_m x_m - \\ &-T_1 \left(x_m + Q_{REF} R_m^T A_1^T \left(A_1 y_m + A_2\right)\right). \end{aligned} \quad (13)$$

III. THE SYNTHESIS OF CONTROL CIRCUIT MODEL OF THE VEHICLE

We consider a model of the vehicle on the basis of the equations of kinematics and dynamics of a rigid body [3, 4]

$$\begin{aligned} \dot{y} &= R(y) x \\ \dot{x} &= M^{-1}\left(F_u + F_d\right) \end{aligned} \quad (14)$$

Where y is the vector of linear and angular positions of a mobile vehicle in the external coordinate system; x is the vector of linear and angular velocities of a mobile vehicle in the body coordinate system; $R(y)$ is matrix of kinematics; M is the matrix of the inertial parameters ; F_u is the vector of control forces and moments ; F_d is the vector of miscellaneous forces and moments acting on the mobile vehicle.

Matrix $R(y)$ and vector F_d structurally coincides to the matrix $R(y_m)$ and vector F_{dm} respectively.

By analogy with the expression (6) will form the control goal for the vehicle in the form

$$\Psi_V = x + QR^T A_1^T \left(A_1 y + A_2\right) \quad (15)$$

We complete the model of the vehicle (15) with integrator:

$$\dot{z} = \Psi_V - \Psi_{VREF}, \quad (16)$$

We introduce the error of the position-trajectory control circuit in the following form

$$e = x + QR^T A_1^T \left(A_1 y + A_2\right) - x_m - Q_{REF} R_m^T A_1^T \left(A_1 y_m + A_2\right) + Bz \quad (17)$$

Where B is matrix of coefficients of controller tuning.

Demand that error control (17) comply with the following reference equation

$$\dot{e}+T_1 e=0\,, \qquad (18)$$

Time derivative the expression (18) considering equations (1), (13) - (15) is equal to

$$\begin{aligned}\dot{e}=M^{-1}\left(F_u+F_d\right)+Q\dot{R}^T\left(y\right)A_1^T\left(A_1 y+A_2\right)+\\ +QR^T\left(y\right)A_1^T A_1 Rx-\dot{x}_m-Q_{REF}\dot{R}_m^T\left(y\right)A_1^T\times\\ \times\left(A_1 y_m+A_2\right)-Q_{REF}R_m^T\left(y\right)A_1^T A_1 R_m x_m+\\ +B\left(\Psi_V-\Psi_{VREF}\right)\end{aligned} \qquad (19)$$

We substitute expressions (17), (19) in equation (18), obtain an algebraic equation, determined that for the vector F_u

$$\begin{aligned}F_u=-F_d+M\{-Q\dot{R}^T\left(y\right)A_1^T\left(A_1 y+A_2\right)-\\ -QR^T\left(y\right)A_1^T A_1 Rx+\dot{x}_m+Q_{REF}\dot{R}_m^T\left(y\right)\times\\ \times A_1^T\left(A_1 y_m+A_2\right)+Q_{REF}R_m^T\left(y\right)A_1^T A_1 R_m x_m-\\ -B\left(\Psi_V-\Psi_{VREF}\right)-T_1 e\}\\ \dot{x}_m=-Q_{ЭТ}\dot{R}_m^T A_1^T\left(A_1 y_m+A_2\right)-Q_{ЭТ}R_m^T A_1^T A_1 R_m x_m-\\ -T_1\left(x_m+Q_{ЭТ}R_m^T A_1^T\left(A_1 y_m+A_2\right)\right).\end{aligned} \qquad (20)$$

Consider the quadratic function of the form

$$V=0.5e^T e\,. \qquad (21)$$

Time derivative the function (21) taking into account equations (1), (13) - (15), (19), (20) is equal

$$\begin{aligned}\dot{V}=e^T\dot{e}=-\begin{Bmatrix}x+QR^T A_1^T\left(A_1 y+A_2\right)-x_m-\\ -Q_{REF}R_m^T A_1^T\left(A_1 y_m+A_2\right)+Bz\end{Bmatrix}^T\times\\ \times T_1\begin{Bmatrix}x+QR^T A_1^T\left(A_1 y+A_2\right)-x_m-\\ -Q_{REF}R_m^T A_1^T\left(A_1 y_m+A_2\right)+Bz\end{Bmatrix}\end{aligned} \qquad (22)$$

Thus, taking into account Barbashin-Krasovskii additions, closed-loop control (1), (9) and (13) - (15), (20) is asymptotically stable in Lyapunov terms.

Thus in the control algorithm (9), (20) operation of kinematics matrix $R(y)$ and $R(y_m)$ conversion is absent, i.e., the specified control algorithm can be applied at arbitrary pitch angles of the vehicle.

Structure of adaptive position-trajectory control system (1), (9), (13) - (15) and (20) is shown in Fig. 1.

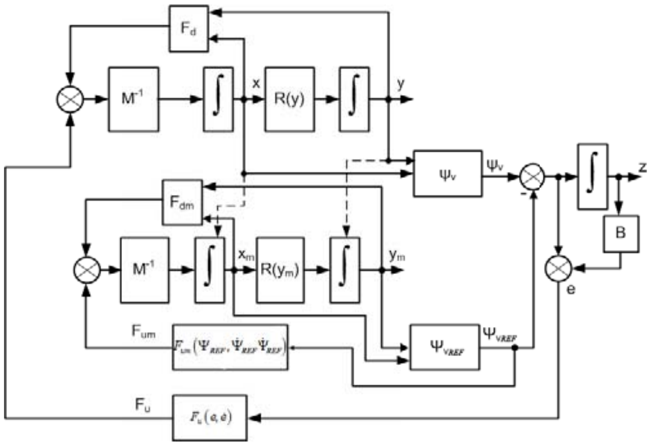


Figure 1. Structure adaptive positional and trajectory control system

The structure in Fig. 1 shows that reference model generates a nominal trajectory of controlled vehicle. Position-trajectory algorithm performs the trajectory as tracking system. The adaptation is carried out by integral component. Note that in this structure, the behavior of the reference model is not corrected, it is assumed that desired trajectories of the vehicle is predefined.

Structure of control system provides cascade connection of reference model loops. It allows changing the settings of each of loops independently of each other. It can be shown by analyzing the closed-loop system with slowly varying angles of orientation of a vehicle. In this case, the kinematics matrix $R(y)$ and $R(y_m)$ are constant and the equation of a closed-loop system with respect to the zeroth position are the following

$$\begin{aligned}&\dot{y}=Rx\\ &\dot{x}=-\left(B+T_1\right)QR^T A_1^T A_1 y-\left(B+T_1+QR^T A_1^T A_1 R\right)x-\\ &-T_1 Bz+BQ_{REF}R_m^T A_1^T A_1 y_m+Bx_m \qquad (22)\\ &\dot{z}=QR^T A_1^T A_1 y+x-Q_{REF}R_m^T A_1^T A_1 y_m-x_m\\ &\dot{y}_m=R\left(y_m\right)x_m\\ &\dot{x}_m=-T_1 Q_{REF}R_m^T A_1^T A_1 y_m-\left(T_1+Q_{REF}R_m^T A_1^T A_1 R_m\right)x_m\end{aligned} \qquad (23)$$

The characteristic equation of system (23) has the form

$$\begin{aligned}D(s)=\det\begin{pmatrix}s^3E+\left(T_1+B+QR^T A_1^T A_1 R\right)s^2+\\ +\left(T_1 B+\left(T_1+B\right)QR^T A_1^T A_1 R\right)s+\\ +T_1 BQR^T A_1^T A_1 R\end{pmatrix}\times\\ \times\left(s^2E+\left(T_1+Q_{REF}R_m^T A_1^T A_1 R_m\right)s+T_1+Q_{REF}R_m^T A_1^T A_1 R_m\right)=\\ =\det\left(sE+T_1\right)\left(sE+QR^T A_1^T A_1 R\right)\left(sE+B\right)\times\\ \times\left(sE+T_1\right)\left(sE+Q_{REF}R_m^T A_1^T A_1 R_m\right)\end{aligned} \qquad (24)$$

Thus, the characteristic equation (24) is the multiplication of reference model adaptation loop and vehicle control loop. Herewith part of the roots of the characteristic equation depends on the matrices $R(y)$ and $R(y_m)$.

This fact is explained by the requirement not to use the calculation of the inverse matrices from the kinematics matrices.

IV. THE SIMULATION RESULTS

Fig. 2 shows the simulation results of the synthesized adaptive control system (1), (9), (13) – (15), (20).

Simulation was performed for the following parameters and matrices of controlled vehicle and controller:

$$R=\begin{bmatrix} A & 0 \\ 0 & A_{\omega} \end{bmatrix}$$

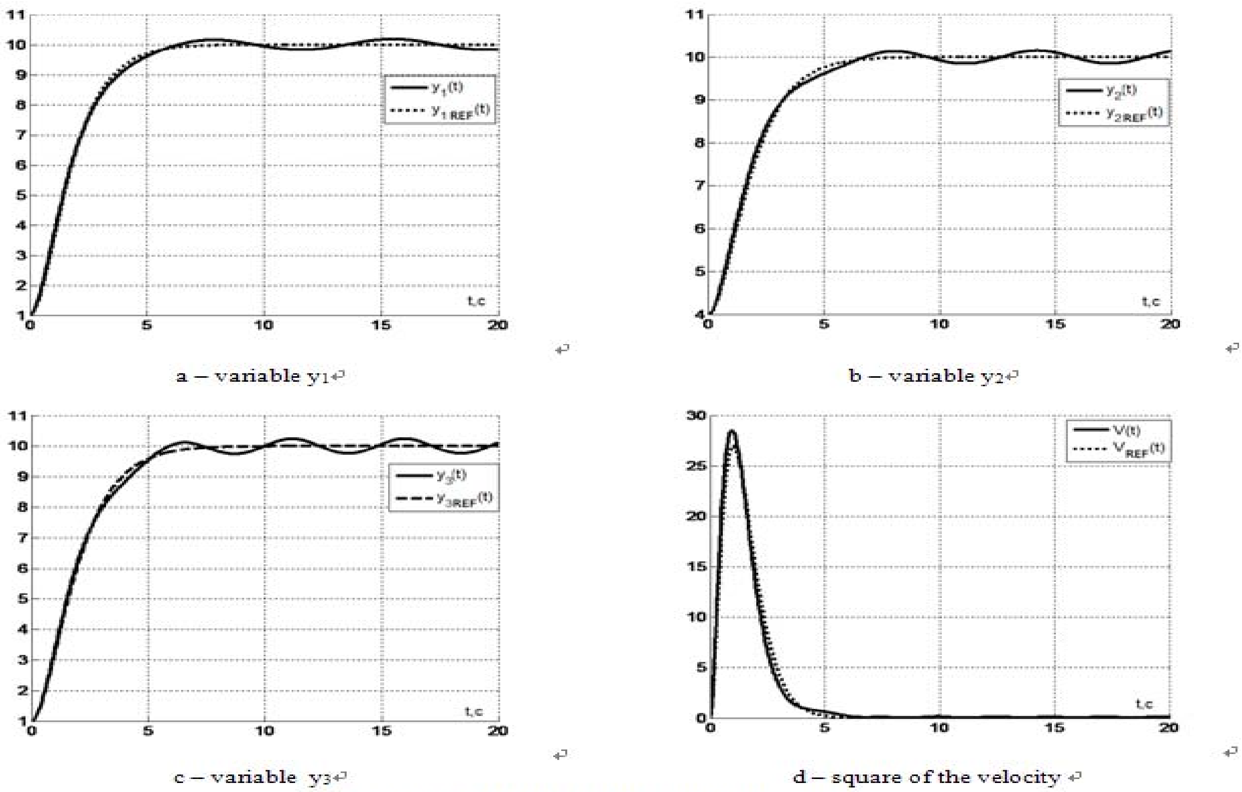
$$A=\begin{bmatrix} \cos\psi\cos\vartheta & -\cos\psi\sin\vartheta\cos\gamma+\sin\psi\sin\gamma & \cos\psi\sin\vartheta\sin\gamma+\sin\psi\cos\gamma \\ \sin\vartheta & \cos\vartheta\cos\gamma & -\cos\vartheta\sin\gamma \\ -\sin\psi\cos\vartheta & \cos\psi\sin\gamma+\sin\psi\sin\vartheta\cos\gamma & \cos\psi\cos\gamma-\sin\psi\sin\vartheta\sin\gamma \end{bmatrix},$$

$$\Delta F_d=\begin{bmatrix} 18\cos(0.8t) \\ 10+15\sin(t) \\ 25\sin(1.3t) \\ 0 \\ 30\sin(t) \\ 0 \end{bmatrix},\ A_{\omega}=\begin{bmatrix} 0 & \dfrac{\cos\gamma}{\cos\vartheta} & -\dfrac{\sin\gamma}{\cos\vartheta} \\ 0 & \sin\gamma & \cos\gamma \\ 1 & -tg\vartheta\cos\gamma & tg\vartheta\sin\gamma \end{bmatrix},$$

$$M=\begin{bmatrix} 5 & 0 & 0 & 0 & 0 & 0 \\ 0 & 5 & 0 & 0 & 0 & 0 \\ 0 & 0 & 5 & 0 & 0 & 0 \\ 0 & 0 & 0 & 10 & 0 & 0 \\ 0 & 0 & 0 & 0 & 100 & 0 \\ 0 & 0 & 0 & 0 & 0 & 100 \end{bmatrix},\ F_d^0=F_{dm}=\begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix},\ A_2=\begin{bmatrix} -10 \\ -10 \\ -10 \\ 0 \\ -2.0 \\ 0 \end{bmatrix},$$

$$T_1=I,\ Q_{REF}=Q=I,\ A_1=I,\ B=10I,$$

Where I is the identity matrix of dimension 6×6.



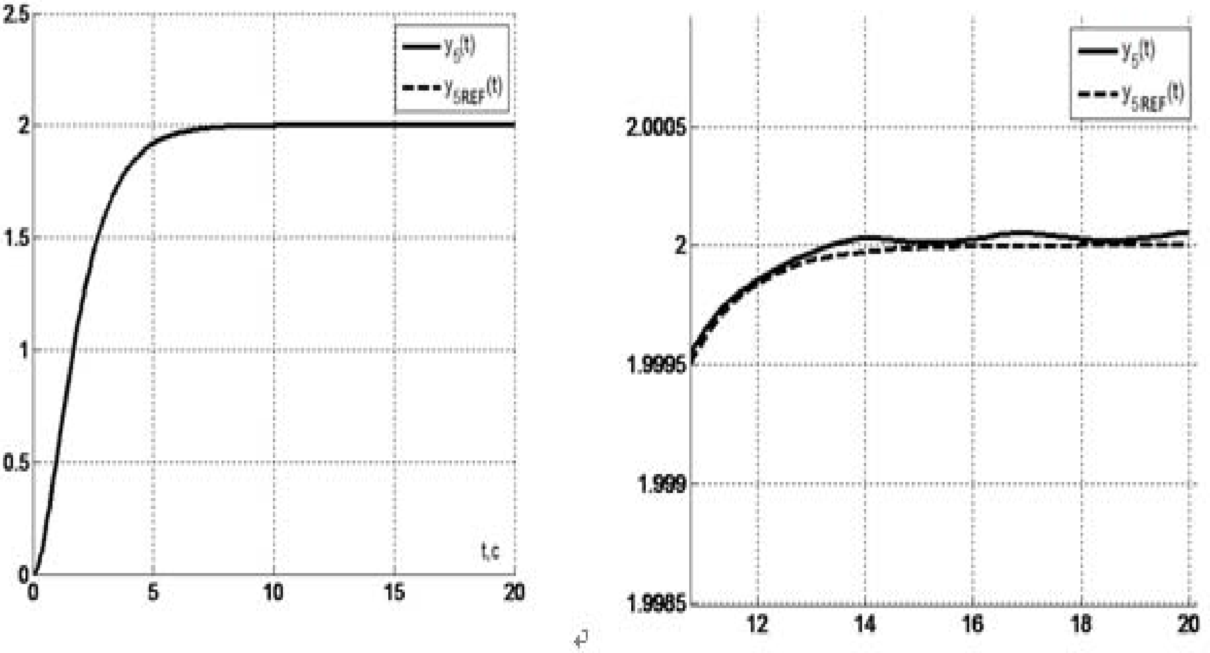
a – variable y1

b – variable y2

c – variable y3

d – square of the velocity

Figure 2. The results of the simulation of adaptive system.



a – the pitch angle y_5 b – pitch angle plot sample

Figure 3. Change the pitch angle of the vehicle.

Fig. 3 shows plots of pitch angle. One can see that the system performs positioning of a vehicle at an angle of pitch of 2.0 radians, decreasing during movement at an angle of π/2 radians. Pitch angle is disturbed.

Plots of variables of Fig. 2 clearly indicates oscillations, caused by harmonic disturbances. However, these oscillations can be made sufficiently small by increasing the values of the matrix adaptation B of controller. This is evident if we write the transfer function of a closed-loop system from disturbance:

$$W_f(s)=\frac{y(s)}{\Delta F_d(s)}=\frac{RM^{-1}s}{(s+T_1)(s+QR^TA_1^TA_1R)(s+B)}. \quad (25)$$

Disturbance suppression is provided by the matrix B, because matrices T_1, Q define desired coordinates and may be changed only by the top level of control.

We denote that the reference model (23) has no feedback, hence the denominator of the transfer function (25) has the third order.

V. Conclusion

In this paper we solve the problem of adaptive positioning of vehicle in the presence of nonmeasurable disturbances. Adaptive system is applied for solving the problem, the basic control law is synthesized on the basis of position-trajectory control and the adaptation is carried out in the frame of searchless systems with reference models. The proposed algorithm of adaptive control differs with proportional-integral algorithm of tracking for the reference model and the procedure for the synthesis of base controller, which allows not to inverse kinematics matrix of the vehicle. Feedback for the reference model is drawn with dashed lines in the structure of Fig. 1. This feedback means a correction of the initial conditions on the reference model on the basis of sensor data. This correction can be carried out only at the initial time or continuously. For example, when moving in an environment with obstacles or performing docking desired trajectory of the vehicle is given strictly. In the case of deviation, the system should provide a return on a given vehicle trajectory. In this case the system is a generator of a desired trajectory and tracking subsystem with a PI-adaptation. If the deviation from the trajectory is allowed (for example, when moving away from obstacles), we can build reference trajectory from the current point. In this case, the correction of of initial conditions for reference model is produced continuously and closed-loop system is fundamentally different from the tracking system.

The analysis showed that the synthesized of closed-loop system is asymptotically stable in the Lyapunov terms. That allows, in difference to [8, 12, 23] separate tuning reference model loop, adaptation loop and basic control loop of vehicle. Well-known algorithms [15 - 22] can be used for tuning of parameters of adaption loop.

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