Robust Output Control Algorithm for a Twin-Rotor Non-Linear MIMO System

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Abstract: This paper addresses to the problem of a non-linear MIMO systems control. A class of non-linear parameter uncertain systems operating under unknown bounded disturbances is considered. It is assumed, that mathematical model of such system can be decomposed on linear and non-linear dynamics. Proposed control algorithm is based on the method of consecutive compensator. The only required parameter to be known for the controller synthesis is a relative degree of linear part of plant. The effectiveness of the control method is demonstrated experimentally using the laboratory platform named «Twin Rotor MIMO System». The proposed method is compared with standard PID controller. Experimental results show that the transient behaviour of the developed control algorithm provides higher accuracy and performance, especially for the case of model parameters deviation from their nominal values.

1 INTRODUCTION

Modern technology development requires to consider different complex mechatronic and robotic systems as real technical objects, which are described by systems of non-linear differential equations, have uncertain parameters and unaccounted dynamics in mathematical models, operate under external and internal disturbances. For such systems classical control methods (modal control, PID control, etc.) are often inapplicable or not capable to meet necessary technical requirements. This problem is especially acute for a class of nonlinear and multivariable systems with sufficient couplings.

The main interest of development of advanced control approaches satisfying these challenges is to improve performance of such devices and extend their application area.

This paper considers control problem for twin rotor MIMO system (TRMS) (Feedback instruments Ltd., 1998). There are a lot of articles proposing different control methods applied in the area of non-linear MIMO systems and applied to a TRMS particularly, see (Rahideh et al, 2008).

Linear and nonlinear PID control algorithms are analyzed in (Cajo, 2015).

Optimal controller using LQR technique is proposed in (Pandey and Laxmi, 2015). Suboptimal controller using iterative linearization algorithm is proposed in (Vrazhevsky and Kremlev, 2015).

Suboptimal tracking controller using a linear quadratic regulator (LQR) with integral action and adaptive sliding mode controller is described in (Phillips, 2014). Another control algorithm based both on optimization method and on fuzzy logic method was designed in (Allouani et al, 2012).

In (Juang et al, 2011) a fuzzy PID control scheme with a real-valued genetic algorithm (RGA) was proposed. A control technique based on controller named «fuzzy-sliding and fuzzy-integral-sliding controller» (FSFISC) is designed and applied to the TRMS in (Tao et al, 2010). Fuzzy controllers is a quite an intensive research area with a set of result in non-linear MIMO systems applications (Shi, 2014).

In (Basri et al, 2014) adaptive controller based on on the backstepping technique was applied to quadrotor that was described as non-linear MIMO system.

A robust control solution is applied to a linearizable non-linear MIMO systems in (Liu and Söffker, 2014). It uses feedback linearization and state feedback control with a disturbance rejection.

However, all considered solutions have a number of disadvantages, such as complicated engineering

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realization, state vector knowledge, complicated adjustment of control parameters. Some researches describe modelling methods including identification and linearization techniques, see (Nejjari et al, 2012). In (Radac et al, 2014.) iterative data-driven algorithm for experiment-based tuning of controllers for nonlinear systems was presented.

In this paper a robust output control method is proposed to control the TRMS system. The control algorithm is based on the consecutive compensator method. Performance of proposed method is based on its possibility to compensate a wide class of external disturbances and save plant stability in conditions of unaccounted internal dynamics. The algorithm is simple to implement due to the fact, that the only parameter required to build the controller is a plant's relative degree.

The paper is organized as follows. Section 2 is devoted to a brief description of the non-linear twin rotor MIMO system. Section 3 contains mathematical model of TMRS bench. Designed control algorithm is presented in Section 4. Finally, Experimental results of the proposed control system and its comparison with PID controller are shown in Section 5. Finally, concluding remarks are given in Section 6.

2 BENCH DESCRIPTION

Consider the non-linear twin rotor MIMO system (TRMS) and obtain its mathematical model. TRMS is a laboratory helicopter-like system with two degrees of freedom and opportunity of independent two-channel control. General view of TRMS is shown on Fig. 1.

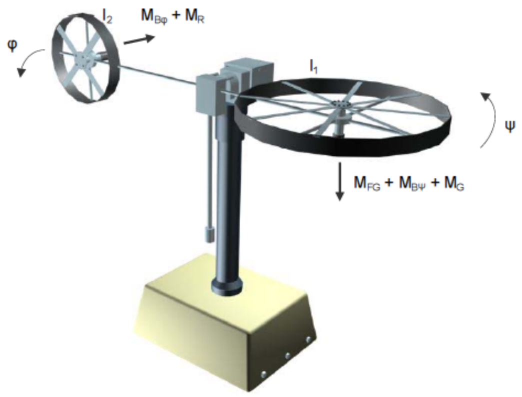

Figure 1: General view of Twin Rotor MIMO System.

Table 1: TRMS parameters.

Parameter description		*Value*	*Units (SI)*
I_1	Pitch inertia moment	6.12×10^{-2}	kg×m^2
I_2	Yaw inertia moment	2×10^{-2}	kg×m^2
M_{g1}	Gravity moment coefficient	0.32	N×m
M_{g2}	Gravity moment coefficient	0.48	N×m
a_1	Parameter of main rotor static charactetistic	1.35×10^{-2}	N/A
b_1	Parameter of main rotor static charactetistic	9.24×10^{-2}	N/A
a_2	Parameter of main rotor static charactetistic	2×10^{-2}	N/A
b_2	Parameter of main rotor static charactetistic	9×10^{-2}	N/A
$B_{1\psi}$	Friction forces moment parameter	6×10^{-2}	N×m×s/rad
$B_{2\psi}$	Friction forces moment parameter	1×10^{-2}	N×m×s/rad
$B_{1\varphi}$	Friction forces moment parameter	6×10^{-3}	N×m×s/rad
$B_{2\varphi}$	Friction forces moment parameter	1×10^{-3}	N×m×s/rad
K_{gy}	Gyroscopic forces parameter	5×10^{-2}	s/rad
k_1	Main rotor gain coefficient	1.1	N/A
k_2	Tail rotor gain coefficient	0.8	N/A
T_{11}	Main rotor parameter	1.1	N/A
T_{10}	Main rotor parameter	1	N/A
T_{21}	Tail rotor parameter	1	N/A
T_{20}	Tail rotor parameter	1	N/A
k_c	Cross-reaction gain coefficient	-0.2	N/A
T_p	Cross-reaction moment parameter	2	N/A
T_0	Cross-reaction moment parameter	3.5	N/A

Full list of its parameters is given on Table 1. These include inertia moments, coefficients of friction forces moment and gravity moments, cross-reaction moment parameters, etc.

The system comprises two DC motors: one of them provides movement in vertical plane (pitch angle) and the other one is for motion in horizontal plane (yaw angle). TRMS is controlled by independent voltage levels on the armature of the motors. The pitch and yaw angles are measurable outputs.

Maximum angles of the plant rotation are limited by mechanical structure constraints. Input voltage levels are limited within the [-2.5V; +2.5V].

Detailed description of the laboratory bench with its mathematical model synthesis is given in (Feedback Instruments, 1998).

3 TRMS MATHEMATICAL MODEL

In this section we present mathematical model description of the bench in form of two third-order differential equations and in a vector-matrix form.

The TRMS works under the following forces: DC motors torques, gravity forces, friction forces and such coupling effects as gyroscopic moment and cross-reaction force.

The plant can be represented as two coupled subsystems. Given mathematical description of the plant also include DC motor transfer functions and friction forces moments.

Plant dynamics in vertical plane is described by the following moment equation

$$I_1\ddot{\psi} = M_1 - M_{FG} - M_{B\psi} - M_G, \quad (1)$$

where ψ is a plant pitch angle, I_1 is an inertia moment, M_1 is a plant torque generated by the main rotor torque τ_1, M_{FG} is a gravity moment, $M_{B\psi}$ is a friction forces moment, M_G is a gyroscopic moment. These moments are represented as follows

$$\begin{cases} M_{FG} = M_{g1}\sin\psi - M_{g2}\cos\psi \\ M_G = K_{gy}M_1\dot{\varphi}\cos\psi \\ M_{B\psi} = B_{1\psi}\dot{\psi} + B_{2\psi}\mathrm{sign}(\dot{\psi}) \\ M_1 = a_1{\tau_1}^2 + b_1\tau_1 \end{cases} \quad (2)$$

DC motors dynamics approximated by first order transfer function can be represented as

$$\begin{cases} \tau_1 = \dfrac{k_1}{T_{11}s + T_{10}}u_1 \\ \tau_2 = \dfrac{k_2}{T_{21}s + T_{20}}u_2 \end{cases} \Rightarrow \begin{cases} \dot{\tau}_1 = \dfrac{k_1}{T_{11}}u_1 - \dfrac{T_{10}}{T_{11}}\tau_1 \\ \dot{\tau}_2 = \dfrac{k_2}{T_{21}}u_2 - \dfrac{T_{20}}{T_{21}}\tau_2 \end{cases}, \quad (3)$$

where τ_1 and τ_2 are the torques generated by DC motors, u_1 and u_2 are the input voltages of the motors.

Taking into account (2) and (3), the dynamics in vertical plane (1) can be represented as follows

$$\begin{cases} \dot{\psi} = \omega_\psi, \\ \dot{\omega}_\psi = -\dfrac{M_{g1}}{I_1}\sin(\psi) + \dfrac{M_{g2}}{I_1}\cos(\psi) - \\ -B_{1\psi}\omega - B_{2\psi}\mathrm{sign}(\omega_\psi) + \dfrac{b_1}{I_1}\tau_1 + \\ +\dfrac{a_1}{I_1}{\tau_1}^2 + K_{gy}M_1\dot{\varphi}\cos\psi, \\ \dot{\tau}_1 = -\dfrac{T_{10}}{T_{11}}\tau_1 + \dfrac{k_1}{T_{11}}u_1, \end{cases} \quad (4)$$

where ω_ψ is a vertical angular speed of the plant.

Rewrite system (4) in the form

$$\begin{gathered} \dddot{\psi} + B_{1\psi}\ddot{\psi} = \theta_{1\psi}k_1u_1 + \tilde{f}_\psi, \\ \tilde{f}_\psi = \theta_{2\psi}k_1u_1 - \frac{M_{g1}}{I_1}\cos(\psi) - \frac{M_{g2}}{I_1}\sin(\psi) + \\ +K_{gy}M_1\dot{\varphi}\cos\psi + B_{1\psi}\mathrm{sign}(\omega_\psi), \end{gathered} \quad (5)$$

where $\theta_{1\psi}$, $\theta_{2\psi}$ and $B_{1\psi}$ are transition coefficients, $\tilde{f}_\psi$ is a function which contains all non-linear components of the plant dynamic in vertical plane.

System (4) in vector-matrix form can be represented as following

$$\begin{cases} \dot{x} = A_\psi x + B_\psi u_1 + F_\psi, \\ y = C_\psi x, \end{cases} \quad (6)$$

where

$$A_\psi = \begin{bmatrix} 0 & 1 & 0 \\ 0 & -B_{1\psi} & \dfrac{b_1}{I_1} \\ 0 & 0 & -\dfrac{T_{10}}{T_{11}} \end{bmatrix}, B_\psi = \begin{bmatrix} 0 \\ 0 \\ \dfrac{k_1}{T_{11}} \end{bmatrix}, \quad (7)$$

$$C_\psi = [1 \quad 0 \quad 0],$$

$$\begin{gathered} F_\psi = \begin{bmatrix} 0 \\ -\frac{M_{g1}}{I_1} \\ 0 \end{bmatrix}\sin(\psi) + \begin{bmatrix} 0 \\ \frac{M_{g2}}{I_1} \\ 0 \end{bmatrix}\cos(\psi) + \\ + \begin{bmatrix} 0 \\ -B_{2\psi} \\ 0 \end{bmatrix}\mathrm{sign}(\omega_\varphi) + \begin{bmatrix} 0 \\ \frac{a_1}{I_1} \\ 0 \end{bmatrix}{\tau_1}^2 + \begin{bmatrix} 0 \\ K_{gy} \\ 0 \end{bmatrix}M_1\dot{\varphi}\cos\psi, \end{gathered} \quad (8)$$

where F_ψ is a vector-function of non-linear components of the subsystem that related with vertical plant dynamics.

Repeat analog calculations for plant dynamics in horizontal plane. Moment equation is represented as follows

$$I_2\ddot{\varphi} = M_2 - M_{B\varphi} - M_R, \quad (9)$$

where φ is a plant yaw angle, I_2 is an inertia moment, M_2 is a plant torque generated by the tail rotor torque τ_2, $M_{B\varphi}$ is a friction forces moment, M_R is a cross-reactions moment. These moments are represented as shown

$$\begin{cases} M_R = \frac{k_c(T_0 s+1)}{T_p s+1}\tau_1, \\ M_{B\varphi} = B_{1\varphi}\omega + B_{2\varphi}\text{sign}(\omega_\varphi), \\ M_2 = a_2{\tau_2}^2 + b_2\tau_2. \end{cases} \quad (10)$$

Considering (3) and (10), the dynamics in horizontal plane (9) can be represented as follows

$$\begin{cases} \dot{\varphi} = \omega_\varphi, \\ \dot{\omega}_\varphi = -B_{1\varphi}\omega - B_{2\varphi}\text{sign}(\omega_\varphi), \\ +\frac{b_2}{I_2}\tau_2 + \frac{a_2}{I_2}{\tau_2}^2, \\ \dot{\tau}_2 = -\frac{T_{20}}{T_{21}}\tau_2 + \frac{k_2}{T_{21}}u_2, \\ \dot{x}_{M_R} = \frac{k_c}{T_p}\left(1 - \frac{T_0}{T_p}\right)\tau_1 - \frac{1}{T_p}x_{M_R}, \end{cases} \quad (11)$$

where ω_φ is a horizontal angular speed of the system, x_{M_R} is a cross reaction variable.

System (11) can be represented as following:

$$\dddot{\varphi} + B_{1\varphi}\ddot{\varphi} = \theta_{1\varphi}k_2u_2 + \tilde{f}_\varphi,$$
$$\tilde{f}_\varphi = \theta_{2\psi}k_1u_1 + B_{2\varphi}(\text{sign}(\omega_\varphi)) + \rho(\tau_1), \quad (12)$$

where $\theta_{1\varphi}, \theta_{2\varphi}$ and $B_{1\varphi}$ are transition coefficients, $\tilde{f}_\varphi$ is a function which contains all non-linear components and cross-reactions of the plant dynamic in vertical plane:

System (11) in vector-matrix form can be represented as following

$$\begin{cases} \dot{x} = A_\varphi x + B_\varphi u_2 + F_\varphi, \\ y = C_\varphi x, \end{cases} \quad (13)$$

where

$$A_\varphi = \begin{bmatrix} 0 & 1 & 0 \\ 0 & -B_{1\varphi} & \frac{b_2}{I_2} \\ 0 & 0 & -\frac{T_{20}}{T_{21}} \end{bmatrix}, B_\varphi = \begin{bmatrix} 0 \\ 0 \\ \frac{k_2}{T_{21}} \end{bmatrix}, \quad (14)$$
$$C_\varphi = [1 \quad 0 \quad 0],$$

$$F_\varphi = \begin{bmatrix} 0 \\ -B_{2\varphi} \\ 0 \end{bmatrix}\text{sign}(\omega_\varphi) + \begin{bmatrix} 0 \\ \frac{a_2}{I_2} \\ 0 \end{bmatrix}{\tau_2}^2 + $$
$$+ \begin{bmatrix} 0 \\ \frac{k_cT_0}{T_p} \\ 0 \end{bmatrix}\tau_1 + x_{M_R}, \quad (15)$$

where F_φ is a vector-function of non-linear components and cross-reactions of the subsystem that related with horizontal dynamics of the plant.

As the result, TRMS mathematical model is represented by two subsystems (5) and (12) with couplings given as bounded external disturbances.

4 ROBUST CONTROL METHOD

In this section we propose control algorithm for previously obtained mathematical model of TRMS. The control law is based on consecutive compensator (Bobtsov, A., 2002) method.

Consider multivariable control plant:

$$Q_i(p)y_i(t) = R_i(p)u_i(t) + \tilde{f}_i(t,y,u) +$$
$$+d_i(t) + \sum_{i=1,i\neq j}^{2} c_{ij}(p)y_j(t) + \sum_{j=1,i\neq j}^{2} \gamma_{ij}(p)u_j(t), \quad (16)$$

where, $i = 1,2, j = 1,2,$ $Q_i(p)$ and $R_i(p)$ are linear differential operators with dimensions n_i and m_i respectively, $y_i(t) \in R$ is an output signal, $u_i(t) \in R$ is an input signal, $\tilde{f}_i(t,y,u)$ is a function of non-linear components in each channel, $d_i(t)$ is a functions of external unknown bound disturbances in each channel, $c_{ij}(p)$ and $\gamma_{ij}(p)$ are linear differential operators of output and input couplings respectively, $p = d/dt$ is a differential operator, $\rho_i = n_i - m_i \geq 1$ is a relative degree of the plant.

A reference model is described by equation:

$$Q_{mi}(p)y_{mi}(t) = R_{mi}(p)u_{mi}(t), i = 1, 2 \quad (17)$$

where $Q_{mi}(p)$ and $R_{mi}(p)$ are linear differential operators, $y_{mi}(t) \in R$ is an output signal of reference model, $u_{mi}(t) \in R$ is a smooth bounded reference signal.

It is necessary to provide tracking of plant's output for the reference model output.

Introduce decentralized consecutive compensator control law in accordance with (Pyrkin, A., et al, 2015):

$$u_i(t) = -\alpha_i K_i(p)\hat{e}_i(t), \quad (18)$$

where α_i is a positive number, $K_i(\lambda)$ is a Hurwitz polynomial with degree $\rho_i - 1$, λ is a complex variable, $\hat{e}_i(t)$ is an estimation of tracking error $e(t) = y_i(t) - y_{mi}(t)$.

For error estimation the observer is used

$$\begin{cases} \dot{\xi}_i = \sigma_i\Gamma_i\xi_i + \sigma_iB_ie_i, \\ \hat{e}_i = L_i^T\xi_i, \end{cases} \quad (19)$$

where $\xi_i \in R^{\rho-1}$ is an observer state vector,

$$\Gamma_i = \begin{bmatrix} 0 & I_{\rho_i} \\ -k_1 & -k_{\rho_{i-1}} \end{bmatrix}, B = [0\ 0 \ldots k]^T,$$
$$L_i = [1\ 0 \ldots 0]^T, \quad (20)$$

where Γ_i is a Hurwitz matrix due to the choice of its coefficients, $\sigma_i > 0$ is a sufficiently large number.

In (Pyrkin, A., et al, 2015) it is proved that control law (18) with observer (19) provides convergence of output signal for the reference model output with prespecified accuracy in the case of

Lipshitz function $\tilde{f}_i(t, y, u)$. Moreover, proposed algorithm is robust with respect to the parameter deviations. However, nonlinear functions in (5) and (12) are not Lipshitz function due to the presence of the function $\mathrm{sign}(\cdot)$.

In (Margun, A., and Furtat, I., 2015a) it is proved that controller (18)-(19) provides convergence of tracking error of MIMO system to the limited area in the case of quantized output measurement. The function $\mathrm{sign}(\cdot)$ is Lipshitz everywhere except at the zero point. In the paper (Margun, A., and Furtat, I., 2015a) the control problem is solved for the system (16) in presence of quantized output. In this case the system is exponentially stable with respect to area around zero caused by the quantizer step and disturbance value. Since dynamics of quantizer function is similar to $\mathrm{sign}(\cdot)$ at zero origin we can conclude, that system (16) is exponentially stable with respect to area around origin. Therefore, controller (18) and estimation algorithm (19) provide exponentially convergence of tracking error of TRMS to the bounded area.

5 EXPERIMENTAL RESULTS

To verify the proposed technique experimentally we use the following parameters of the consecutive compensator

$$\alpha_i = 0.5, K_i = 5p^2 + 20p + 50, \sigma_i = 1, \quad i = 1, 2. \tag{21}$$

Observer parameters are taken as

$$\Gamma_i = \begin{bmatrix} 0 & 1 \\ -0.01 & -100 \end{bmatrix}, B_i = [0\ 1]^T, \quad L_i = [1\ 0]^T, \ \ i = 1, 2. \tag{22}$$

Linear part of TRMS within parameters from Table 1 is represented in the following form

$$A_\psi = \begin{bmatrix} 0 & 1 & 0 \\ 0 & -6 * 10^{-2} & 1.51 \\ 0 & 0 & -0,91 \end{bmatrix}, B_\psi = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}, \quad C_\psi = [1 \quad 0 \quad 0], \tag{23}$$

$$A_\varphi = \begin{bmatrix} 0 & 1 & 0 \\ 0 & -6 * 10^{-3} & 4.5 \\ 0 & 0 & -1 \end{bmatrix}, B_\varphi = \begin{bmatrix} 0 \\ 0 \\ 0.8 \end{bmatrix}, \quad C_\varphi = [1 \quad 0 \quad 0], \tag{24}$$

Presented control algorithm is experimentally tested on the TRMS and compared with PID controller. The plant is controlled simultaneously and independently by each degree of freedom. Therefore, all coupling effects are taken into account during the experiments.

Experimental results (Fig. 2 - 9) for each plant subsystem in tracking mode and in stabilization mode are shown in Appendix.

Several scenarios for tracking (Fig. 2 - 5) and stabilization (Fig. 6 - 9) modes are carried out for both control systems. PID controller tuned by TRMS developers is tested in the same modes under the same conditions for evaluation of proposed controller performance.

On Fig.4 and Fig.5 it is apparent that consecutive compensator operates more accurate than PID controller. On Fig.6 and Fig.7 consecutive compensator operates with comparable with PID controller accuracy. On Fig.6 - Fig.9 plant trajectories in stabilization mode are demonstrated. Transient processes of the consecutive compensator and the PID controller are quite similar.

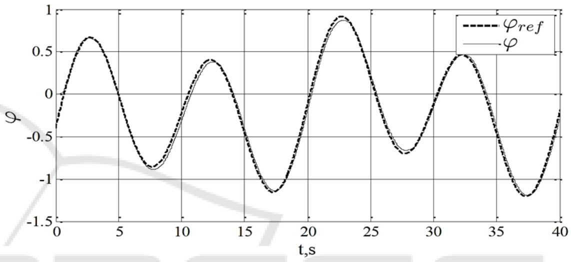

Figure 2: Plant yaw output in tracking mode under the consecutive compensator work.

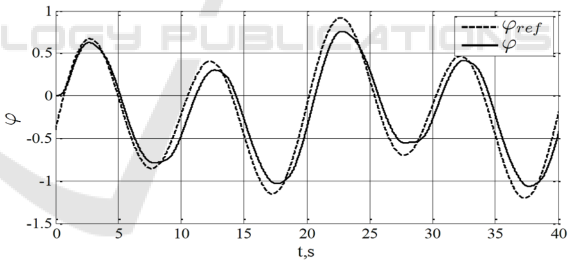

Figure 3: Plant yaw output in tracking mode under the PID controller work.

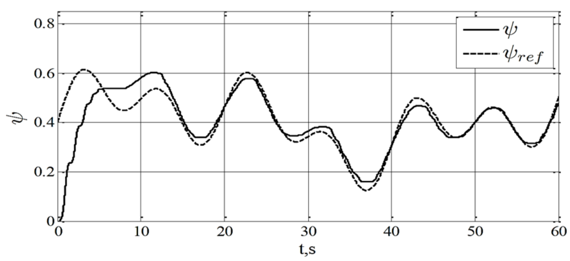

Figure 4: Plant pitch output in tracking mode under the consecutive compensator work.

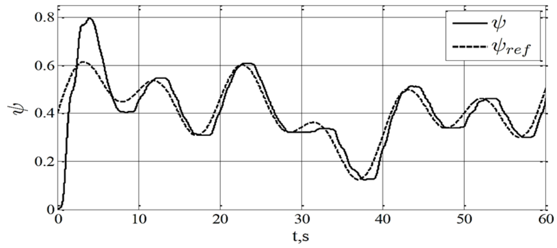

Figure 5: Plant pitch output in tracking mode under the PID controller work.

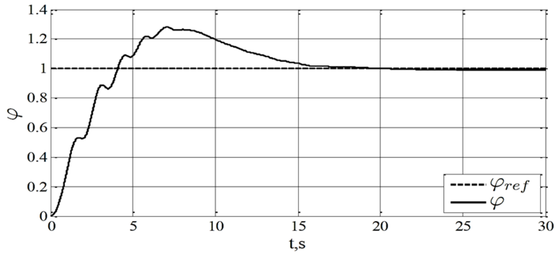

Figure 6: Plant yaw output in stabilization mode under the consecutive compensator work.

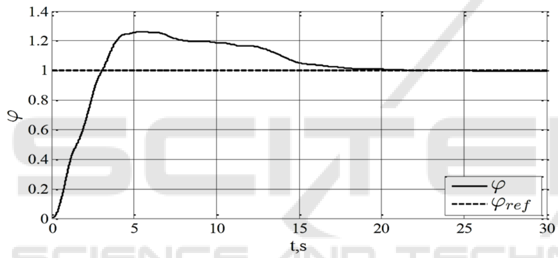

Figure 7: Plant yaw output in stabilization mode under the PID controller work.

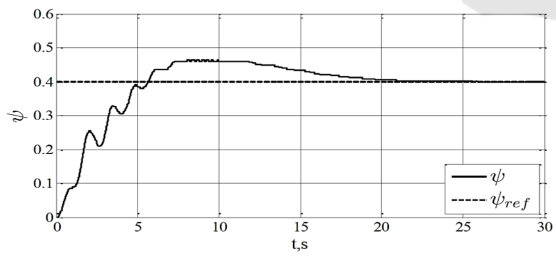

Figure 8: Plant pitch output in stabilization mode under the consecutive compensator work.

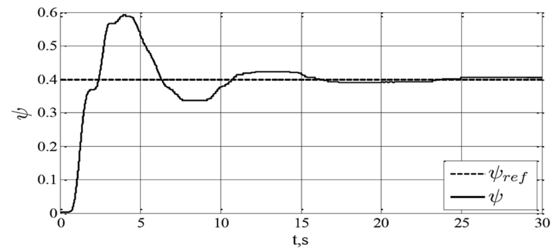

Figure 9: Plant pitch output in stabilization mode under the PID controller work.

Experimental results analysis revealed that robust output control was successfully applied to the chosen plant and its quality exceeds the PID controller.

6 CONCLUSIONS

In this paper we present control algorithm for non-linear parameter uncertain MIMO systems operating under unknown bounded disturbances. A key assumption for application of the control law is that mathematical model of the system can be decomposed on linear and non-linear dynamics. Relative degree of the linear part of plant is the only required parameter for the proposed controller.

Introduced robust control algorithm is applied to the laboratory platform named «Twin Rotor MIMO System» and provides its exponential stability with convergence to a bounded zero origin. Non-linear part of the TRMS that contains cross-relations of the plant is considered as unknown bounded disturbance. Designed control system is tested experimentally and compared with the standard PID controller. Several scenarios of TMRS work are held and experiments demonstrate that proposed control algorithm provides higher performance and accuracy of the laboratory bench. It should be noted that presented control algorithm is robust with respect to parametric disturbances that is supported by experimental results.

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