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SYNTHESIS OF ANGULAR MOTION CONTROL LOOP FOR UNMANNED AERIAL VEHICLE

Ua Стаття розкриває особливості синтезу контурів керування кутовим рухом безпілотного літального апарату (БПЛА). У межах даного дослідження розраховані робастні регулятори для всіх можливих висот і швидкостей польоту. Також були визначені діапазони зміни параметрів руху БПЛА, для яких якість керування залишається прийнятною. Стаття містить обмеження на амплітудно-частотні характеристики і вагові функції.

Ru Статья раскрывает особенности синтеза контуров управления и угловым движением беспилотного летательного аппарата (БПЛА). В рамках данного исследования рассчитаны робастные регуляторы для всех возможных высот и скоростей полета. Также были определены диапазоны изменения парамет-

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ров движения БПЛА, для которых качество управления остается приемлемым.

Рассматривается работа двух типов регулятора. Первый из них формирует управляющее воздействие по отклонению от заданного угла. Второй имеет две отдельные передаточные функции: по задающему воздействию и по текущему значению угла. Регулятор с двумя входными величинами обеспечивает более высокое быстродействие, отсутствие перерегулирования в переходном процессе, более широкий диапазон изменения скорости полета, при котором качество управления остается приемлемым. Запасы устойчивости в системе, работающей только по отклонению, значительно меньше, чем в системе с регулятором второго типа. Преимуществом управления по отклонению является простота реализации. В контурах обоих типов астатически подавляется моментное возмущение.

Для синтеза корректирующих устройств использовался 2-Риккати подход. Статья содержит ограничения на амплитудно-частотные характеристики и весовые функции.

Introduction

The requirements for the quality of unmanned aerial vehicles (UAVs) motion control can be significantly different depending on the performed tasks [1, 2]. For highly maneuverable UAVs, the requirements for response speed and dynamic accuracy are especially strict. Moreover, their motion parameters, which determine the main aerodynamic characteristics, can quickly change during flight [2]. The control laws of such aircraft must quickly change their parameters or be insensitive to parametric disturbances due to rudeness. Robust regulators can best meet these requirements, as well as ensure ease of control laws implementation and high system reliability [3, 4].

Formulation of the problem

We will consider the problem of synthesizing roll angle robust control laws for an unmanned aerial vehicle and studying their performance over a wide range of speed changes.

Control object

The aircraft is equipped with a solid fuel engine and aerodynamic controls. To stabilize the roll angle of the UAV, the corrective device generates a signal that controls the servo using the deviation of the measured angle from the set angle (fig. 1).

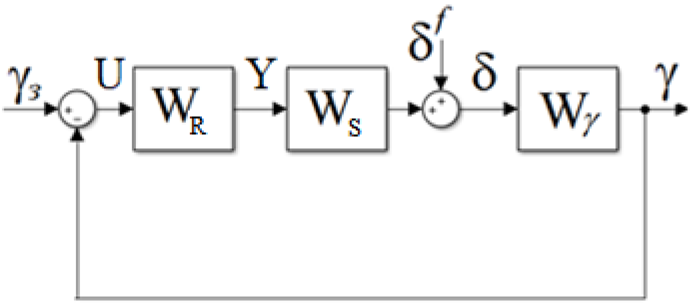

Fig. 1. Block diagram of the roll angle control channel

In fig. 1 W_γ is the transfer function of the aircraft for a roll angle γ; W_R is the transfer function of the corrective device; δ is the rotation angle of the aerodynamic control surface; δ^f is a disturbance; γ_3 is a reference signal. The transfer function of the servo drive W_S is a second-order unit with a time constant of 0,01 s and a pure time delay of 0,005 s.

The same parameters of the control object transfer function W_γ can take values that differ many times depending on the choice of trajectory. In addition, they change rapidly during a flight. For altitude of 11500 m and speed of 629 m/s

$$W_\gamma = \frac{1657}{s^2 + 0{,}9726s}, \tag{1}$$

where s is the Laplace variable. For speed of 314 m/s $W_\gamma = \frac{737{,}2}{s^2 + 0{,}667s}$, and in the first second of flight $W_\gamma = \frac{177{,}4}{s^2 + 0{,}4971s}$.

Synthesis of the corrective device for the roll angle control loop

The corrective device W_R should provide a transition time of not more than 0,5 s, overshoot up to 30 %, as well as first-order astatism with satisfactory stability margins and limited deflections of control surface. In addition, it is necessary to fend off the disturbance δ^f reduced to the dimension of the control surface rotation angle.

It is possible to satisfy all these requirements, as well as provide the necessary robustness with respect to parametric perturbations, using the H_∞ theory [5].

The regulator for the roll channel ensures that the inequality

$$\left\| \begin{matrix} W_{31}\Phi_{ge3} & W_{31}\Phi_{fe3}W_{33} \\ W_{32}\Phi_{gu3} & W_{32}\Phi_{fu3}W_{33} \end{matrix} \right\|_{\infty} \le 1 \tag{2}$$

is met. Here $\Phi_{ge3} = \dfrac{\gamma_3(s) - \gamma(s)}{\gamma_3(s)}$; $\Phi_{gu3} = \dfrac{\delta(s)}{\gamma_3(s)}$; $\Phi_{fu3} = \dfrac{\delta(s)}{\delta^f(s)}$; $\Phi_{fe3} = \dfrac{\gamma_3(s) - \gamma(s)}{\delta^f(s)}$; W_{31}, W_{32}, W_{33} are weight functions.

The search of W_R was carried out using the 2-Riccati approach [5]. For object (1), a representation of the corrective device in the state space is obtained:

$$\begin{aligned} \dot{X} &= AX + BU; \\ Y &= CX + DU, \end{aligned} \tag{3}$$

where X is the state vector; Y is the output value of the corrective device (control signal); U is the input value of the corrective device.

For the nominal point (1), we obtain the parameters of the equations (3) of the roll angle channel corrective device:

$$A = \begin{pmatrix} -1367 & 578.6 & -1.5\cdot 10^4 & -1127 & 2.623\cdot 10^6 \\ -667 & 7,501 & -1712 & -129,5 & 2,996\cdot 10^5 \\ 0,5386 & -3,934 & 13,04 & 4,653 & -2668 \\ -0,5028 & 4,636 & -10,58 & -4,501 & 1824 \\ -32,14 & 4,216 & -61,52 & 473,1 & -2,691\cdot 10^5 \end{pmatrix};$$

$$B = \begin{pmatrix} 2,273\cdot 10^4 \\ 2596 \\ -24,6 \\ 12,31 \\ 304,7 \end{pmatrix}; \tag{4}$$

$$C = \begin{pmatrix} -2,579 & 1,116 & -29,48 & -2,215 & 5156 \end{pmatrix}; \quad D = 44,69.$$

In this case, weight functions

$$W_{31}(s) = \frac{707,9\,s + 1,413\cdot 10^4}{1000\,s + 14,13}; \quad W_{32}(s) = \frac{94,87\,s + 1,897\cdot 10^4}{0,9487s + 6\cdot 10^4},$$

and the quality criterion (2) turned out to be 0,9704.

A significant influence on the synthesis process of W_R is exerted by the need to disturbance δ^f suppress (Fig. 3). For W_R those satisfying criterion (2), the transition process in the roll angle control channel ends in 0,4 s and has the overshoot of 23 % (Fig. 4). At the same time, the aerodynamic control body is able to react correctly on reference signal of up to 35 ° (Fig. 5).

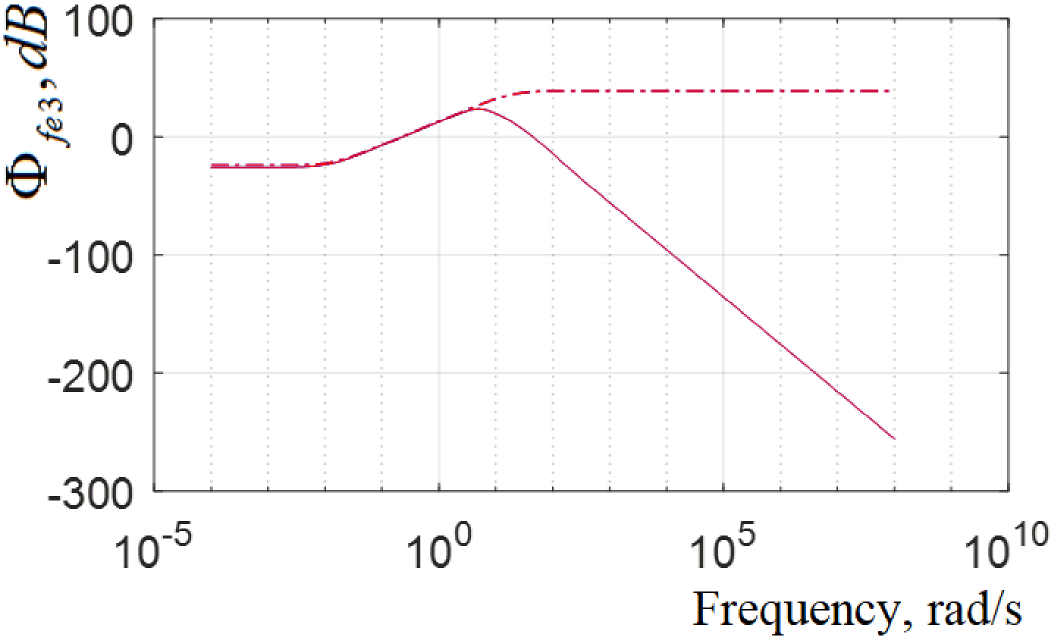

Fig. 3. Frequency response of the roll angle control channel on disturbance

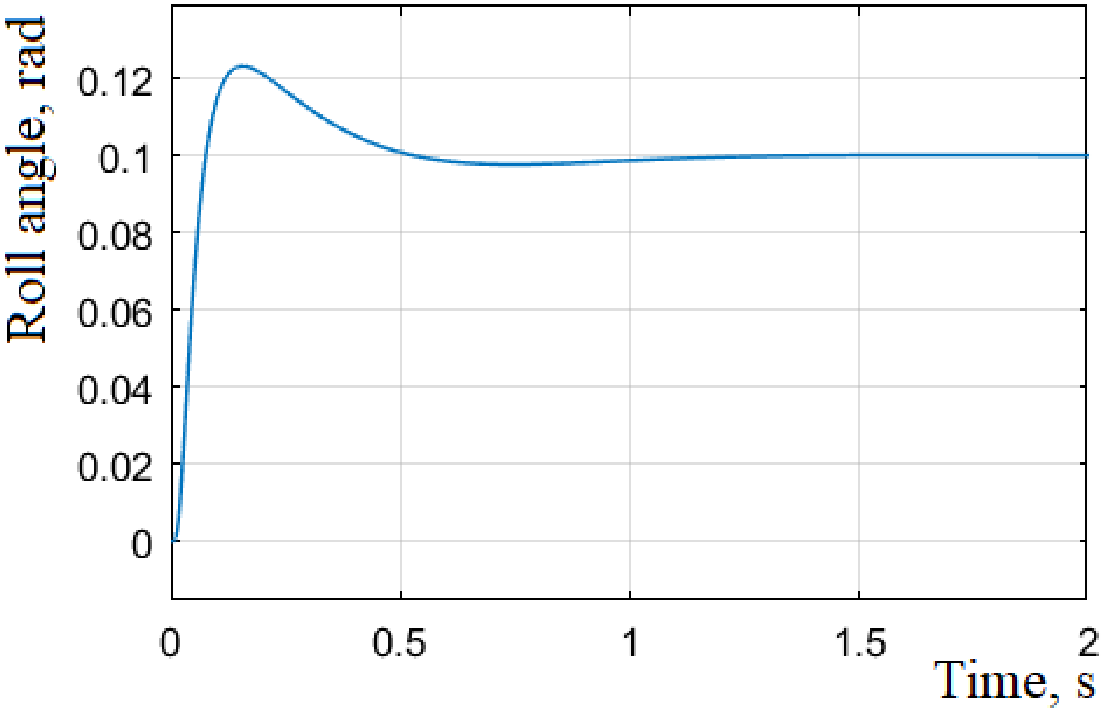

Fig. 4. Transition process in the roll angle control channel

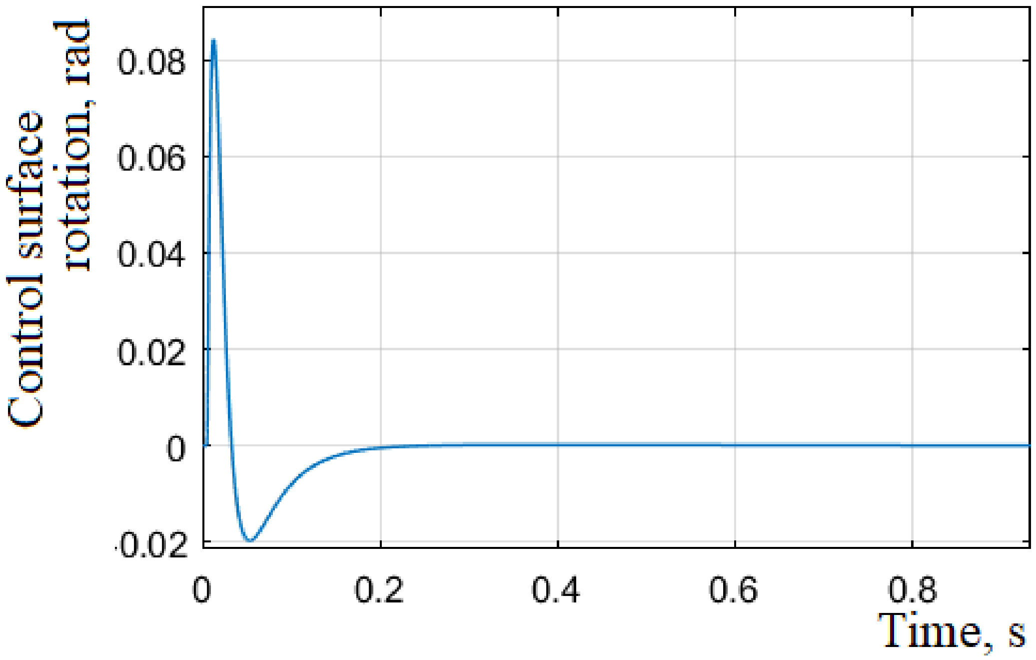

Fig. 5. Control body work with a stepped reference signal of 0,1 rad

Such a corrective device satisfies the requirements for control quality when flying at the altitude of 11500 m for Mach numbers M = 1,55–3,9. With an increase in speed within the indicated limits, the transition process ends faster, however, overshoot increases and stability margins decrease (Fig. 6). When flying at the speed of 1151 m/s, the transition process ends in 0,3 s and has an overshoot of 29 % (Fig. 6).

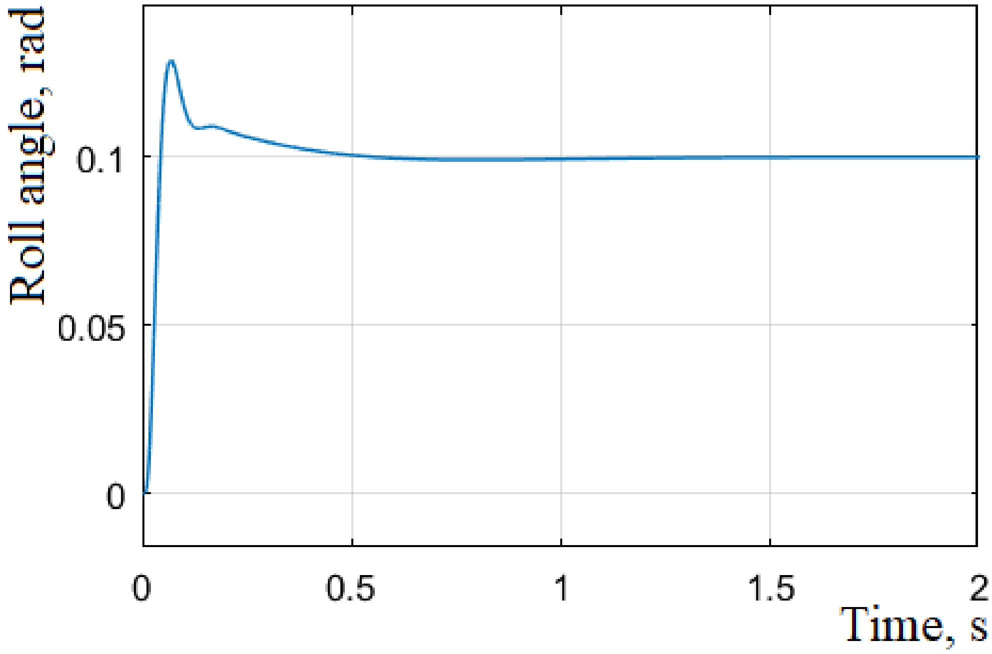

Fig. 6. The transition process in the roll angle control channel at M = 3,9

Roll angle control loop without overshoot in transition process

The roll angle transition process has overshoot in all sections of the possible flight paths. Its presence is undesirable if the yaw angle is controlled through the roll loop. To eliminate overshoot, it is necessary to change the structure of the control system (Fig. 1).

In the roll angle control loop with a monotonic transition process (Fig. 8), the corrective device has two transfer functions: from the reference signal and from the current roll angle (Fig. 7). Then in equations (3) $U = (\gamma_3, \quad \gamma)^T$.

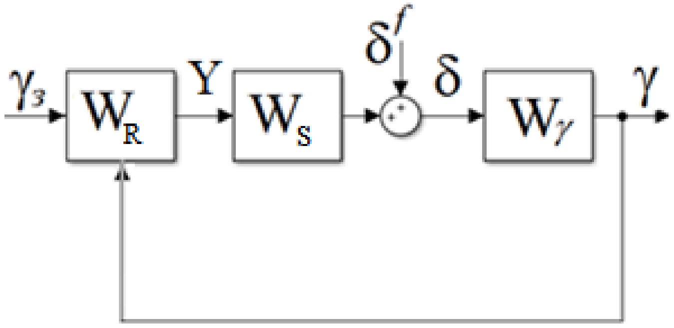

Fig. 7. The block diagram of the control channel without overshoot

For such a block diagram, at the nominal point (1), we obtain a sixth-order regulator with parameters:

$$A = \begin{pmatrix} -441.3 & 270.1 & -287.6 & 7699 & 1.405\cdot10^4 & 3.079\cdot10^6 \\ -560.6 & -27.19 & -35.34 & 860.3 & 1666 & 3.423\cdot10^5 \\ -22{,}34 & 7{,}493 & -2{,}692 & 38{,}24 & 78{,}06 & 1{,}622\cdot10^4 \\ -5{,}106 & 0{,}5942 & 8{,}35 & -46{,}63 & -70{,}96 & -1{,}455\cdot10^4 \\ -2{,}837 & 2{,}261 & 1{,}36 & -41{,}9 & -6{,}321\cdot10^4 & 330{,}7 \\ -5{,}062 & -0{,}4851 & 66{,}69 & -112{,}1 & 1{,}277\cdot10^4 & -1{,}408\cdot10^4 \end{pmatrix};$$

$$B = \begin{pmatrix} 0{,}008854 & -0{,}001318 & -0{,}4443 & 1{,}51 & -0{,}2449 & -80{,}09 \\ 0{,}7135 & -1{,}342 & 1{,}746 & 6{,}547 & 0{,}4319 & 148{,}8 \end{pmatrix}^T;$$

$$C = (0{,}755 \quad -0{,}5094 \quad 0{,}5665 \quad -15{,}13 \quad -27{,}64 \quad -6052);$$

$$D = (0, \quad 0). \tag{5}$$

Thus, the quality criterion (2) turned out to be 0,8767.

At the nominal point (1), the regulator (3) with parameters (5) provides a transition process of 0,16 s duration without overshoot (Fig. 8) in the control loop (Fig. 7).

This corrective device provides the required control quality when flying at the altitude of 11500 m in the range of Mach numbers of 1,06 – 4,33. An increase in flight speed compared to the nominal leads to a decrease in response speed and in stability margins. In this case, the transition process remains monotonic. For lower speeds, starting from M = 1,55, an overshoot appears (Fig. 9).

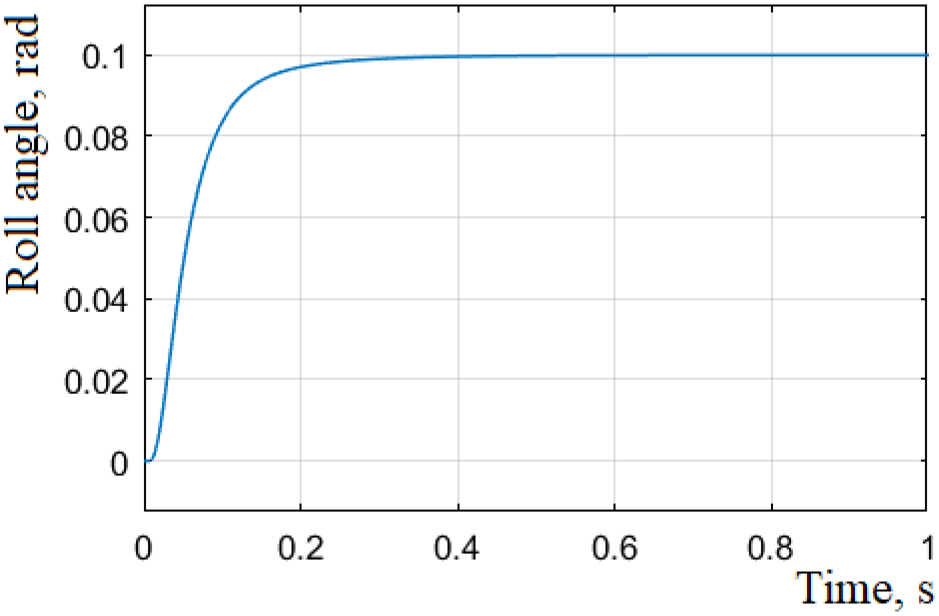

Fig. 8. Monotonic transition process in the roll angle control channel

In addition to higher response speed, in comparison with the regulator (3), (4), the regulator with parameters (5) provides a stronger amplitude suppression of disturbance. However, the process of suppressing disturbance is longer in time (Fig. 10).

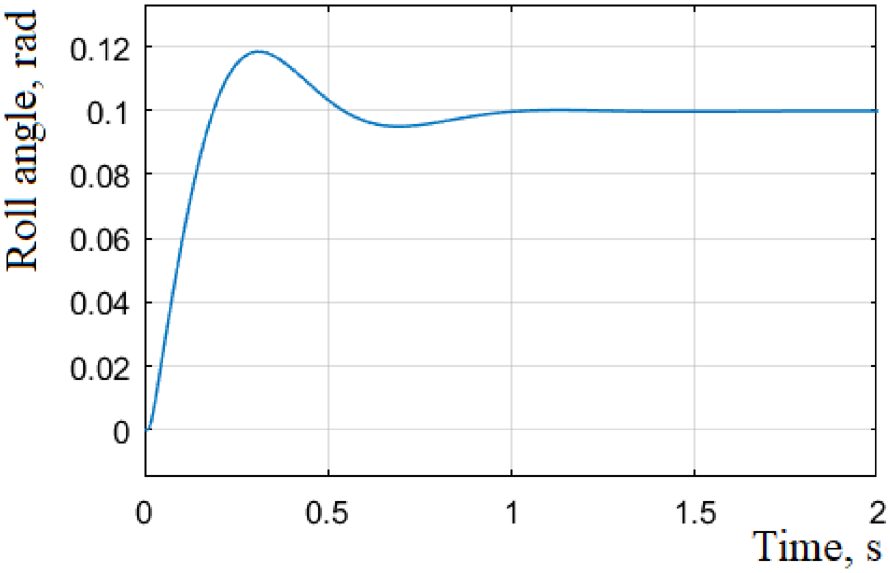

Fig. 9. The transition process in the roll angle control channel at M = 1,06

Thus, control laws were calculated for all trajectories of the aircraft: for horizontal flight at altitudes of 300 – 14000 m for climb, and for descending. To calculate the parameters of the regulators, as well as to obtain the amplitude-frequency characteristics and transition processes, Matlab was used.

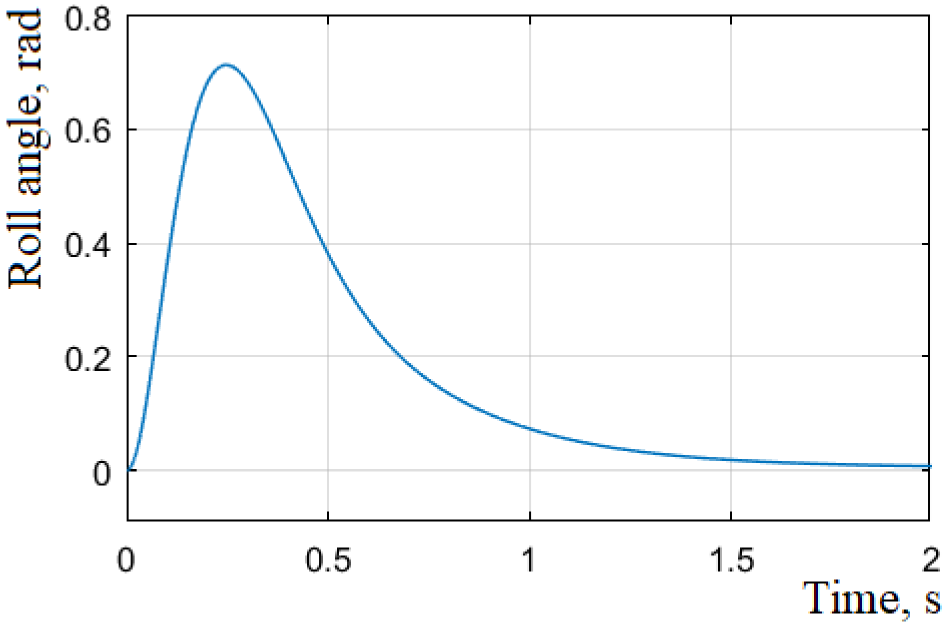

Fig. 10. The process of disturbance suppression

Conclusions

Synthesized corrective devices provide the required control quality of the UAV motion from the time of launch to the end of the flight in the entire range of permissible altitudes and speeds.

The astatic suppression of disturbance in the control loop, which works by deviation, leads to low stability margins, as well as the presence of transition process overshoot. For a horizontal section of the flight path at a given height, such a regulator must be calculated at least at two points.

The use of the control loop, which has separate transfer functions from the reference signal and from the current roll angle, allowed to eliminate overshoot and increase response speed. In addition, such a regulator can provide the required control quality over a wider range of model parameters than a deviation regulator.

The number of points at which it is necessary to carry out the synthesis procedure to ensure the required control quality from the start to the completion of the UAV flight depends on its trajectory. In this case, for the UAV under study, it is necessary to use the regulators obtained in at least four points. More often points have to be taken in areas with low efficiency of control bodies.

Obtained weight functions and restrictions for the amplitude-frequency characteristics can be used as initial values for the synthesis of control systems for other similar aircraft.

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