UDC 629.7.014-519.052.015.3:681.52

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DESIGN OF THE ROBUST PID CONTROL FOR UNCERTAIN NONLINEAR MODEL OF THE UAV USING ARTIFICIAL GAIN AND TIME-DELAY MODEL

Estimations of the flight vehicles aerodynamic coefficients through the theoretical, numerical, wind tunnel and flight-test methods have always errors and uncertainties. Nonlinear dynamics of the unmanned aerial vehicle due to speed variations, as well as variability and uncertainty of the aerodynamic coefficients can be considered as an uncertain model. A robust proportional-integral-derivative controller is designed based on the nonlinear optimization in the time domain for the uncertain nonlinear dynamical model of the unmanned aerial vehicle. Artificial gain and time-delay models are added to achieve required stability margins as system robustness during the robust proportional-integral-derivative control design. The aerodynamic coefficients are divided into two groups on the basis of the output vector's sensitivity to the aerodynamic coefficients. Nonlinear optimization of the criterion is performed in two steps for the robust proportional-integral-derivative controller design. In the first step of the design, nominal values are used for coefficients with low-sensitivity, and upper and lower limits are used only for high sensitive aerodynamic coefficients. In the second step, the upper and lower limits are applied all of the aerodynamic coefficients to evaluate and re-adjust the robust proportional-integral-derivative controller parameters. The robust controller is designed for the uncertain nonlinear roll and lateral dynamic model of the Skywalker X8 flying wing to show the effectiveness of the proposed method to guarantee the stability margins. In the given example during the design of the robust controller, with adding of the artificial gain and time-delay model in the control loop the controller parameters are changed. This regulator increases the phase stability margin by about 10 degrees and the gain stability margin by about two for the family of the equivalent uncertain linear models.

Keywords: *robust proportional-integral-derivative control, unmanned aerial vehicle, uncertain aerodynamic coefficient, linear and nonlinear uncertain dynamic model, optimization, Simulated Annealing algorithm, flying wing.*

Introduction

Proportional-Integral-Derivative (PID) controllers are used in a variety of areas such as industrial, automotive, aerospace, electrical motors, and so on. More than 90% of the control loops have PID control.

Control engineers are faced with a wide range of design requirements. These requirements such as reference tracking, disturbance rejection, robustness, noise attenuation and implementation constraints are contradictory. The complexity and contradictory of the requirements make it difficult to design the control system. Additionally, in real-world applications, there is a tendency to use simple controllers such as PIDs and known structures to facilitate implementation, validation, and re-tuning.

Regardless of the implementation limitations, LMI-based methods have been developed to design a control system for multiple design requirements. These techniques lead to sophisticated controllers that are necessary to reduce order, delete fast dynamics, etc. for implementing. This controller simplification is a difficult problem and sometimes complex controllers cannot be implemented. So recently, research has been conducted on finding optimal parameters for simple controller and PIDs. Different methods for adjusting of the parameters for PID and robust PID controllers such as Ziggler Nichols method, Kappa Tauing Tuning, pole placement, design based on gain and phase margins, interval polynomial method, QFD method, Kharitanov-based methods, Nyquist-based methods, tuning based on the genetic algorithm, loop shaping, and so on were developed [1-4].

In practice, for the design of the UAV control system, the successful control loop closure is usually used [5]. However, nonlinear dynamics of the unmanned aerial vehicle due to speed variations, as well as variability and uncertainty of the aerodynamic coefficients, can be considered as an uncertain model [1, 2, 6, 7]. Adaptive, robust mu-synthesis and robust gain scheduling control methods were applied to the UAVs [1-3, 8].

The command “systune” in the MATLAB software is developed to design the robust controllers with simple structures such as lead, lag and PID controllers. It can be used for the uncertain linear dynamic systems [3, 9].

In this research, robust PID controllers are used and designed simultaneously for the non-linear uncertain dynamic model of the UAV in two stages, based on the optimization of the criterion function in the time domain. To reduce the size of the problem of optimization based on the sensitivity of the output vector to the aerodynamic coefficients, the aerodynamic coefficients are classified into two groups with high and low sensitivity. In the first stage, nominal values for the aerodynamic coefficients with low-sensitivity, and upper and lower limit values for coefficients with high-sensitivity are used. In the second step, the upper and lower limits for all coefficients are considered and coefficients of the controller are evaluated and re-adjusted. Simulating Annealing Optimization Algorithm as a powerful algorithm is used for nonlinear optimization.

In order to achieve the good robustness of the single-input single-output systems, the gain and phase margins are used. Robustness of the multi-input multi-output systems can be applied through the infinity norm of the sensitivity and complementary transfer functions of the closed-loop system [4]. Here artificial gain and time-delay models (GTDM) are added in the control loops to achieve suitable stability margins for the nonlinear UAV dynamic model with robust PID controllers.

Problem is given in the second section. Robust PID controller for the uncertain nonlinear dynamic of the UAV with using artificial GTDMs to guarantee the robustness is discussed in the third section. Fourth section presents robust PID controllers and simulation results for the roll and lateral channels of the Skywalker X8 flying wing. Conclusion and suggested future works are given in final section.

Problem statement

The nonlinear dynamical model with the parametric uncertainty for the UAV can be written as follows:

$$\begin{aligned} \dot{X} &= f(X, P, U, t), \\ Y &= h(X, P, U, t), \end{aligned} \tag{1}$$

where f and h are non-linear functions, X is the state vector with n_X dimension, Y is the output vector with n_Y dimension, U is input vector with n_U dimension, P is the vector of uncertainty parameters and t is time. The upper and lower limits of the elements for vector P are as follows:

$$p_i^- \le p_i \le p_i^+, \; i = 1, 2, ..., n_P, \tag{2}$$

where n_P is the number of the uncertain parameters, p_i^+ and p_i^- are the upper and lower limits of the p_i. Robust PID control parameters are tuned for the nonlinear system with the parameters uncertainty to ensure robust stability and stability to follow reference inputs and to reduce the effect of the disturbance and noise in the presence of control signal constraints, that's mean:

$$\begin{aligned} |U| &\le U_{Max}, \\ |\dot{U}| &\le \dot{U}_{Max}. \end{aligned} \tag{3}$$

Design requirements for the uncertain nonlinear dynamic model of the UAV include:

1. Good reference tracking: error between reference signals and their responses must be minimized.
2. Disturbance rejection: effect of the internal and external disturbances and model uncertainty on the desired outputs must be eliminated.
3. Minimum energy consumption: angle and rate limits of the actuator must be considered during the robust control system design.

Ensuring robustness with the artificial gain and time-delay model

In order to design the robust PID control, nonlinear optimization is used as the dual of the system identification using the output error method. The Integrated Time-Weighted Square Error (ITWSE) criterion is applied to tune the robust control parameters for achieving steady state error for reference signal tracking and disturbance rejection:

$$\begin{aligned} J &= \sum_{j=1}^{2^{N_P}} \sum_{i=1}^{N_S} t(i) \times (J_i), \\ J_i &= (Y_{RM}(i) - Y_j(i))^T Q (Y_{RM}(i) - Y_j(i)) + \\ &+ (U_j(i))^T R_U (U_j(i)) + (\dot{U}_j(i))^T R_{\dot{U}} (\dot{U}_j(i)), \end{aligned} \tag{4}$$

where N_S is the number of the simulation samples, Q is the diagonal weighting matrix with the $n_Y \times n_Y$ dimension, R_U and $R_{\dot{U}}$ are the diagonal weighting matrices of the $n_U \times n_U$ dimension, Y_{RM} is the outputs of the reference model and 2^{N_P} is the total number of cases obtained by combining the upper and lower limits of the uncertain parameters. The reference model is determined based on the design requirements.

Similar to the system identification problem, optimal inputs for reference and turbulence signals are used to obtain rich data for successful nonlinear optimization and robust control design [10]. Filters with suitable bandwidth are used to attenuate the effect of noise. Bandwidth values of the noise filters can be found with the robust control ones.

Kharitonov's theorem is applicable for the linear interval systems but cannot be used for nonlinear system. If the number of the uncertain parameters is increased, then the number of their possible combinations is increased and then the problems of nonlinear optimization and robust control design become more difficult and time-consuming for nonlinear systems. The output vector sensitivity to the uncertain parameters is used to solve the problem of the dimension-increasing. Uncertain parameters are divided into two categories with high and low sensitivity and the design of the PID control system is carried out in two steps. In the first stage, only the uncertainty (upper and lower limits) of the high-sensitivity parameters are used, and for low sensitivity parameters, only the nominal values are used. In the second stage of the design of the control system, the uncertainty of all the parameters is considered and the design of the first stage is evaluated and re-adjusted.

Artificial gain and time-delay models are added in the control loops to achieve appropriate stability margin. Block diagram of the artificial GTDM during robust control system design for the uncertain nonlinear model of the UAV to guarantee required stability margins is shown in Fig. 1.

Robust PID control of the Skywalker X8 roll, and lateral channels

The robust PID control is designed for the nonlinear dynamics model of the Skywalker X8 lateral and roll channels Using the proposed method. The dynamic model of the roll and lateral channels is a non-minimal phase model. With the presence and absence of the GTDM in the control loop, the robust controller parameters are found. A 25 ms time-delay model is used in the design method with the presence of artificial GTDM. The roll and lateral model and parameters of the Skywalker X8 given in [1] are used here. The closed loop system with GTDM is shown in Fig. 2. The objective is to track the reference course angle, χ and reject external disturbances effects on the course and roll (φ) angles with suitable stability margins.

The parameters of the robust PID control system for two design methods are shown in Table 1. The K_{p1} and K_{i1} values are decreased and K_{p2} value is increased in design with the delay model. In other words, with this change in the values of the parameters, the stability margins of the real system (without the GTDM) with the robust PID controller designed in the presence of the GTDM are increased.

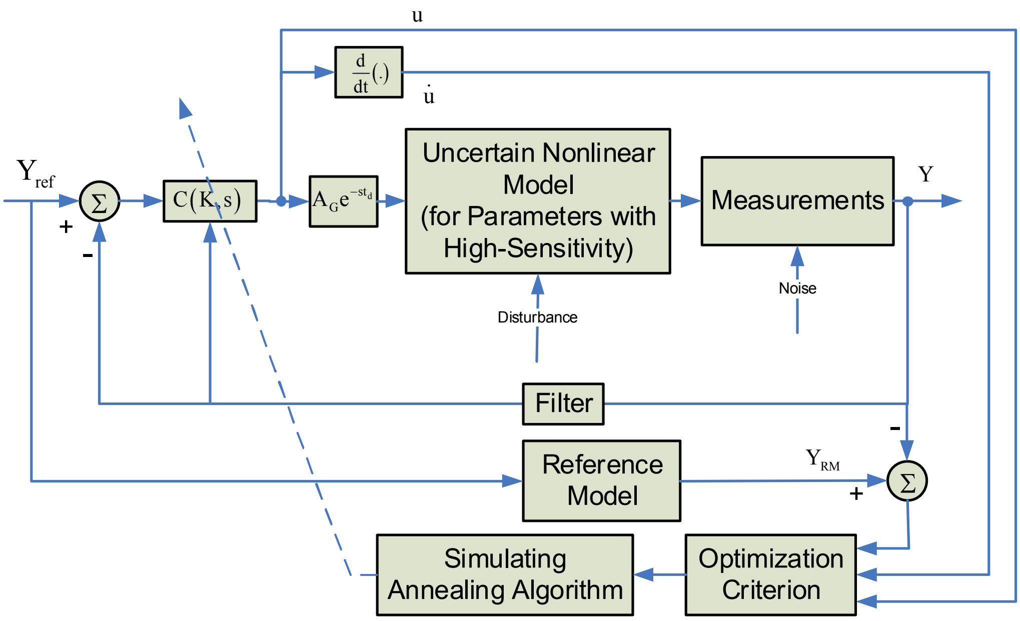

Fig. 1. Using of the artificial GTDM during robust control system design for the uncertain nonlinear model of the UAV to guarantee required stability margins

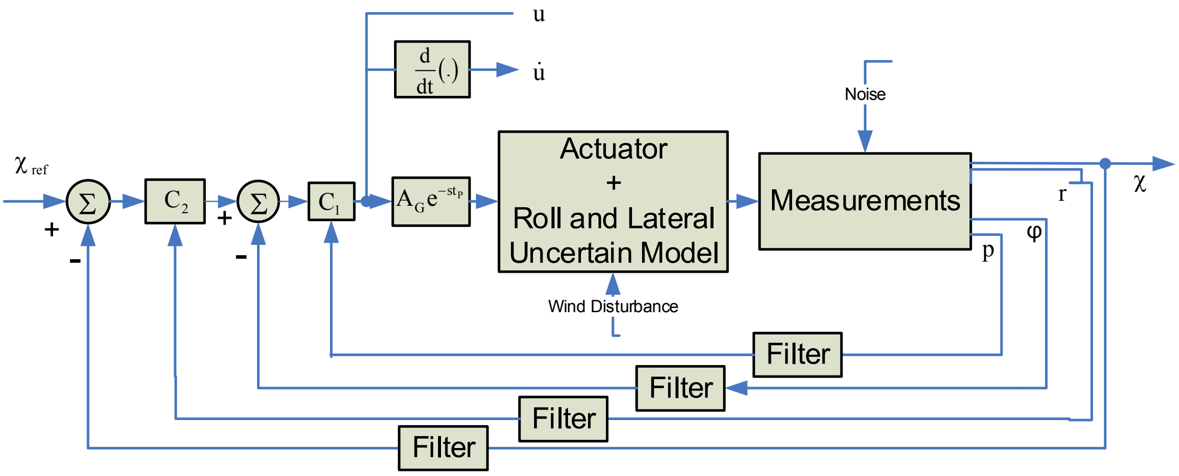

Fig. 2. Robust control for the roll and lateral nonlinear model of the Skywalker X8 with parametric uncertainty with artificial gain and time-delay

The values of the stability margins of the real linearized uncertain system (without GTDM) with the robust controller designed in the presence and absence of GTDM are shown in Fig. 3 and Fig. 4. The gain and phase margins, A_{GM} and φ_{PM} formulas for the family of the uncertain linear systems are as follows:

$$\begin{aligned}
&\arg\left[C(j\omega_p)G_i(j\omega_p)\right] = -\pi \rightarrow \\
&A_{GM} = \frac{1}{\left|C(j\omega_p)G_i(j\omega_p)\right|}, \\
&\left|C(j\omega_g)G_i(j\omega_g)\right| = 1 \rightarrow \\
&\varphi_{PM} = \angle C(j\omega_g)G_i(j\omega_g) + \pi, \\
&i = 1, 2, \ldots, N_P;
\end{aligned} \tag{5}$$

where $G_i(s)$ and $C(s)$ are uncertain system sample and control system transfer functions, ω_p and ω_g are the phase crossover frequency and gain crossover frequency, respectively.

With the robust controller designed in the presence of the artificial GTDM, the stability margins of the real system are increased. The worst case gain and phase stability margins of the actual system (without the presence of the GTDM) or robust control designed (without artificial GTDM) are 6 and 38 degrees, respectively. While the worst case gain and phase stability margins of the actual system (without the presence of the GTDM) for robust control designed (with artificial GTDM) are 8 and 48 degrees, respectively.

The simulation results of the uncertain nonlinear model in the presence of the actuator angle and rate limits with the robust controller (designed without and with artificial GTDM) are shown in Fig. 5 and Fig. 6. It is observed that the uncertain nonlinear system with time-delay model is unstable for some combinations of the uncertainty parameters with the robust controller designed with artificial GTDM.

Table 1

Parameters of robust PID controllers with and without artificial GTDM in the design

Method	Design without time-delay	Design with time-delay
K_{p1}	1.2464	0.9245
K_{i1}	1.7469	1.3369
K_{d1}	0.0078	0.0214
K_{p2}	1.3017	1.4428
K_{i2}	0.0062	0.0001
K_{d2}	0.0229	0.0846

Conclusion

The procedure for designing a robust PID control of the uncertain non-linear model of the UAV was presented based on the optimization of the nonlinear criterion in the time domain. The use of the virtual GTDM was proposed in the robust control design process to guarantee the robustness (stability margins) of the control system.

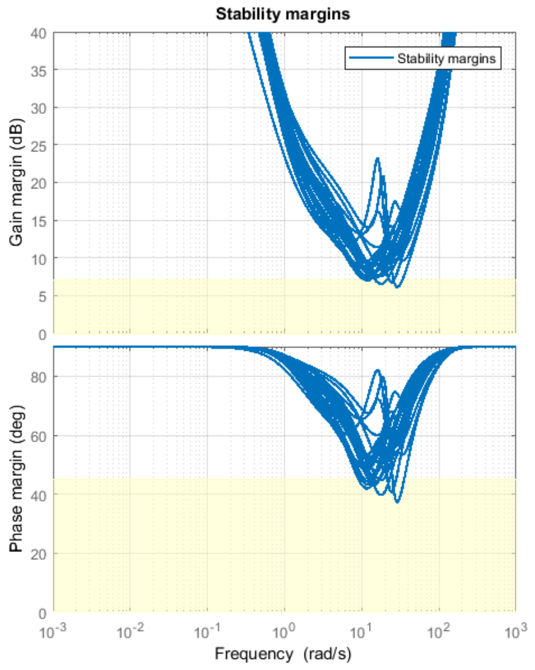

Fig. 3. Stability margins for the real linear uncertain systems (without delay model) for roll and lateral channels with robust PID controller (designed without the presence of artificial GTDMs)

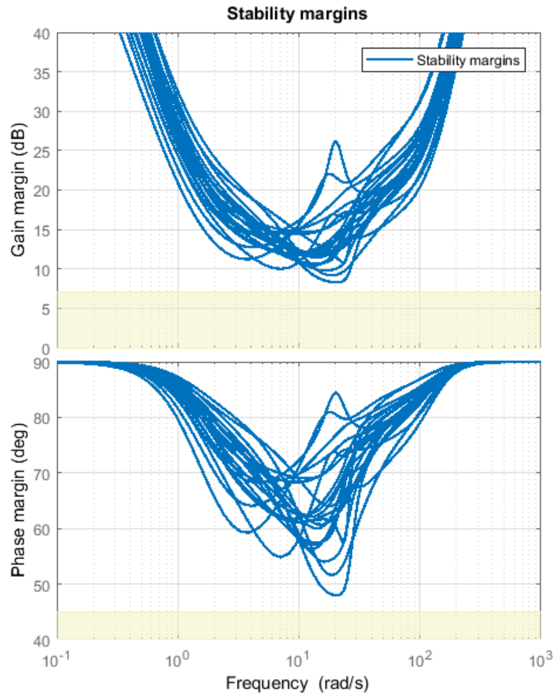

Fig. 4. Stability margins for the real linear uncertain systems (without delay model) for roll and lateral channels with robust PID controller (designed with the presence of artificial GTDMs)

From the sensitivity of the output vector to the uncertain parameters, a two-stage method for robust PID control design was proposed to simplify the nonlinear optimization problem. The robust PID control system was designed and simulated for the nonlinear model of the roll and lateral channels of the Skywalker X8 with using the proposed method to show the increase in the stability margins.

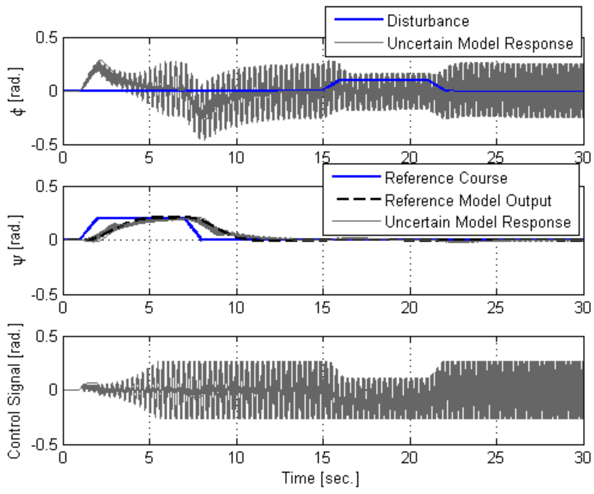

Fig. 5. Simulation of the uncertain nonlinear model of the roll and lateral model (with delay model) with robust PID controller (designed without the presence of artificial GTDMs)

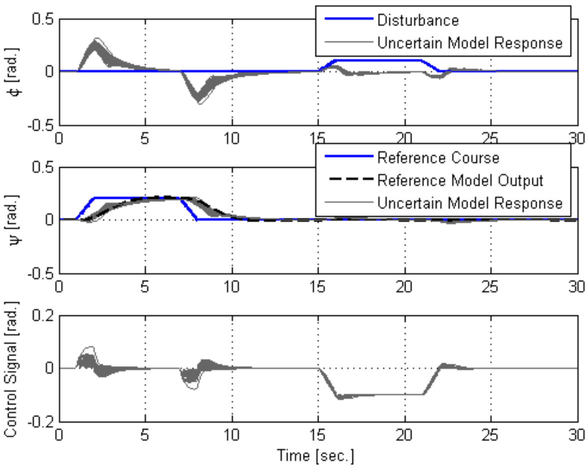

Fig. 6. Simulation of the uncertain nonlinear model of the roll and lateral model (with delay model) with robust PID controller (designed with the presence of artificial GTDMs)

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Поступила в редакцию 2.10.2017, рассмотрена на редколлегии 22.11.2017

СИНТЕЗ РОБАСТНОГО ПІД-РЕГУЛЯТОРА ДЛЯ НЕВИЗНАЧЕНОЇ НЕЛІНІЙНОЇ МОДЕЛІ БПЛА З ВИКОРИСТАННЯМ ШТУЧНОЇ МОДЕЛІ ПОСИЛЕННЯ І ТИМЧАСОВОЇ ЗАТРИМКИ

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Оцінювання аеродинамічних коефіцієнтів літальних апаратів за допомогою теоретичних, чисельних методів, а також в аеродинамічній трубі і на основі льотних випробувань зазвичай має помилки та невизначеності. Нелінійна динаміка безпілотного літального апарату через зміну повітряної швидкості і також невизначеність аеродинамічних коефіцієнтів можуть розглядатися як невизначена модель. На основі нелінійної оптимізації в тимчасовій області для невизначеної нелінійної динамічної моделі безпілотного літального апарату було розроблено робастний пропорційно-інтегрально-похідний регулятор. Штучні зміни у моделі за допомогою посилення і тимчасової затримки застосовуються для досягнення стійкості і якості робастної системи. На основі чутливості вихідного вектору до аеродинамічних коефіцієнтів вони діляться на дві групи. Нелінійна оптимізація критеріїв для синтезу робастного регулятора виконується в два етапи. На першому етапі проектування номінальні значення використовуються для коефіцієнтів з низькою чутливістю, а верхні і нижні межі використовуються тільки для високочутливих аеродинамічних коефіцієнтів. На другому етапі верхні і нижні межі застосовуються до всіх аеродинамічних коефіцієнтів для оцінки і повторного налаштування параметрів робастного регулятора. Щоб показати ефективність запропонованого методу робастний пропорційно-інтегрально-похідний регулятор спроектовано для невизначеної нелінійної динамічної моделі бічного каналу і каналу крену літаючого крила Skywalker X8. З введенням у модель штучного посилення і тимчасової затримки в контурі управління під час проектування робастного пропорційно-інтегрально-похідного регулятора в вирішуваному прикладі параметри регулятора було змінено таким чином, щоб регулятор для сімейства еквівалентних невизначених лінійних моделей збільшував запас стійкості по фазі близько 10 градусів і запас стійкості по амплітуді близько 2 дБ.

Ключові слова: робастне пропорційно-інтегрально-похідне управління, безпілотний літальний апарат, невизначений аеродинамічний коефіцієнт, лінійна і нелінійна невизначена динамічна модель, оптимізація, алгоритм імітації відпалу, літаюче крило.

СИНТЕЗ РОБАСТНОГО ПИД-РЕГУЛЯТОРА ДЛЯ НЕОПРЕДЕЛЕННОЙ НЕЛИНЕЙНОЙ МОДЕЛИ БПЛА С ИСПОЛЬЗОВАНИЕМ ИСКУССТВЕННОЙ МОДЕЛИ УСИЛЕНИЯ И ВРЕМЕННОЙ ЗАДЕРЖКИ

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Оценивание аэродинамических коэффициентов летательных аппаратов с помощью теоретических, численных методов, а также в аэродинамической трубе и на основе лётных испытаний обычно имеет ошибки и неопределённости. Нелинейная динамика беспилотного летательного аппарата из-за изменения воздушной скорости, а также неопределённость аэродинамических коэффициентов могут рассматриваться как неопределённая модель. На основе нелинейной оптимизации во временной области для неопределённой нелинейной динамической модели беспилотного летательного аппарата был разработан робастный пропорционально-интегрально-производный регулятор. Искусственные изменения в модели добавлением усиления и временной задержки применяются для достижения устойчивости и качества робастной системы. На основе чувствительности выходного вектора к аэродинамическим коэффициентам они делятся на две группы. Нелинейная оптимизация критерия выполняется в два этапа для синтеза робастного регулятора. На первом этапе проектирования номинальные значения используются для коэффициентов с низкой чувствительностью, а верхние и нижние пределы используются только для высокочувствительных аэродинамических коэффициентов. На втором этапе верхние и нижние пределы применяются ко всем аэродинамическим коэффициентам для оценки и повторной настройки параметров робастного регулятора. Чтобы показать эффективность предлагаемого метода робастный пропорционально-интегрально-производный регулятор спроектирован для неопределённой нелинейной динамической модели бокового канала и канала крена летающего крыла Skywalker X8. С введением в модель искусственного усиления и временной задержки в контуре управления во время проектирования робастного пропорционально-интегрально-производного регулятора в рассмотренном примере параметры регулятора были изменены таким образом, чтобы регулятор для семейства эквивалентных неопределённых линейных моделей увеличивал запас устойчивости по фазе около 10 градусов и запас устойчивости по амплитуде около 2 дБ.

Ключевые слова: робастное пропорционально-интегрально-дифференциальное управление, беспилотный летательный аппарат, неопределённый аэродинамический коэффициент, линейная и нелинейная неопределённая динамическая модель, оптимизация, летающее крыло.

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