

UDC 533.6.013.42:629.7.025.32:629.762.5
DOI: 10.26467/2079-0619-2020-23-3-52-62

FREQUENCY MODEL OF AN ESSENTIALLY NONLINEAR STEERING DRIVE WITH A DIGITAL MICROCONTROLLER

S.V. GRYZIN^{1,2}

¹ *Dolgoprudny Research and Production Enterprise, Dolgoprudny, Russia*

² *Moscow Aviation Institute (National Research University), Moscow, Russia*

When designing a stabilization system for highly maneuverable unmanned aerial vehicles (UAVs), one of the relevant tasks is to study the operation of the steering drive in the frequency band corresponding to the flexural vibrations of the UAV body. To ensure the stability of the UAV stabilization system, quite conflicting requirements may be imposed on the dynamic characteristics of the drive. In particular, the requirement for a sharp suppression of the amplitude-frequency characteristic at the frequency of UAV bending vibrations with minimal phase distortions in the control band of the longitudinal and lateral channels of the stabilization system can significantly complicate the task of researching the stability of the UAV motion control system. The article discusses an electric drive prototype with a digital microcontroller, designed for a highly maneuverable UAV. Adaptive algorithms of the digital controller make it possible to provide the necessary phase delays in the control frequency band and at the same time almost completely suppress the harmonic components of the control signals at the frequencies of the bending vibrations of the UAV body. The algorithms are essentially nonlinear in nature and are based on a change in the gain of the direct circuit of the drive depending on the frequency of the input signal, which greatly complicates the calculation of the transfer function of the steering drive for use in the frequency model of the stabilization system. Generally, the steering drive is described by a linear minimum-phase system, presented as a transfer function of one of the typical blocks of the first or second order, but for the specified steering drive with given dynamic characteristics, this approach is untenable. As a result of the study, a method for obtaining a frequency model of the steering drive is proposed, which is implemented as a non-minimum phase system, the main property of which is the independence of the amplitude-frequency and phase-frequency characteristics. In the process of research, the results obtained on the proposed model are compared with the results of experiments on a drive prototype and its complete non-linear time model. The main advantage of the proposed frequency model is a fairly simple description of the steering drive in the frequency domain, convenient for use as part of the frequency model of the stabilization system in the study of problems of ensuring the stability of UAV flight.

Key words: unmanned aerial vehicle (UAV), stabilization system, electric drive, frequency responses, digital controller, non-minimum phase systems, frequency model, nonlinear model.

INTRODUCTION

The steering drive is the executive device of the UAV stabilization system and is designed to convert the received input control signals into the proportional flight control turns within the conditions of significant hinge moments caused by the interaction between the aerodynamic flow and the control surfaces. The main challenge for the design of the servomechanisms is to achieve their optimum performance for the given mass and dimension parameters, which are limited by the UAV design features [1–5]. The task is achieved by the maximum possible use of the drive elements forced properties. The basic servomechanism design principles are introduced in a great number of papers, particularly [6–9].

The new generation of electrical servomechanisms are subjected to strict yet conflicting requirements for the frequency band pass value, frequency band pass phase lag, and reducing the mass and dimensions while keeping the power values. Complying with these requirements for the steering drives in conditions of significant destabilizing factors, considering nonlinearities (voltage and current saturation, pitch play, dry friction and viscous frequency) and the object of control unsteadiness is a difficult and multi-objective problem. As a consequence, the electric steering drive control system is increasingly implemented on the basis of microcontrollers with the maximum functions imposed onto the algorithmic level.

As an example of such solutions the research introduces the acting model of the electric drive with the digital microcontroller, which implements the complex nonlinear control algorithms and fea-

tures non typical frequency response compared to steering drives which use the linear control laws. The application of nonlinear algorithms for the steering drive control system is explained by the fact that the implementation of a given abrupt inhibition of the UAV body flexural frequency at tight tolerance for the range of the band pass value and the given phase of the frequency band pass in conditions of parametric disturbances, which is quite challenging and hard to achieve within the minimum linear phase systems. Some examples of discrete non-minimum phase systems application are presented in [10–11].

The sources having been analyzed have shown, that the steering drive control design process is almost always brought to the linear system research methods and, for the cases of a single or double nonlinearity, to the linear approximation of the systems. As the superposition principle cannot act for the nonlinear systems, there is a limited number of descriptive methods in the frequency range for the systems with three or more nonlinearities. Consequently, the research of the digital controller steering drives, which forms the adaptive linear and nonlinear algorithms is mostly performed using complete nonlinear imitation mathematical models.

The paper presents the digital controller drive frequency model obtaining. The digital controller implements the nonlinear adaptive algorithm. The frequency model obtained is convenient for the use in the UAV stabilization system.

RESEARCH METHODS

Let us consider the acting model of the UAV electromechanical steering drive, the dynamic characteristics of which should meet the following requirements

- the frequency band pass not less than 20Hz and not more than 30 Hz;
- frequency band pass phase lag not more than 45°;
- for the frequency band pass more than 35 Hz the values of the Bode amplitude plot should not be less than minus 10 dB.

The main components of the steering drive are: the digital microcontroller, the power actuator, the speed sensor (rate generator), the electric motor, the actuator deflection sensor, the gearbox.

The special features of the mathematical model for the adaptive controller synthesis are shown in [12]. The functional diagram of the full nonlinear model of the electric servomechanism is shown in Figure 1.

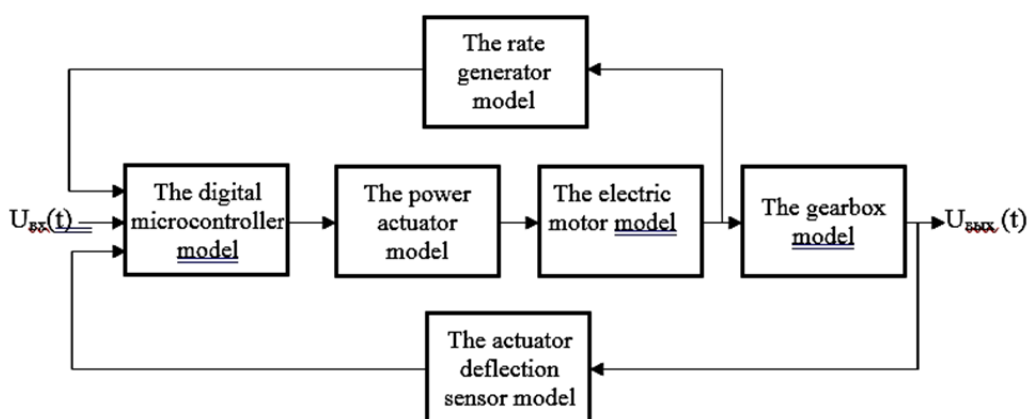


Fig. 1. The functional diagram of the digital servomechanism nonlinear model

The mathematical model presents a system of nonlinear differential (the electromechanical part of the drive) and finite-difference (microcontroller) equations, which connect the drive body input and output. The equation parameters (the microcontroller stroking frequency, the electric motor and rate generator electromagnetic constants, mass moments of inertia, dry friction and viscous frequency, the

gearbox play etc.) correspond to the parameters listed in the steering drive component nameplate data. The equations are integrated using the first order Euler method. This temporary model considers the following essential nonlinearities of the electric drive:

- battery voltage and current saturation,
- microcontroller nonlinearities (digitization, phase lag, nonlinear correction, control signal limitations),
- moments of dry friction and tooth ripples of the executive electric motor,
- play, the gearbox dry friction and viscous frequency moments.

As mentioned above, the superposition principle does not act for nonlinear systems. Accordingly, for the system with three or more nonlinearities there are few descriptive methods in the frequency area at present. The necessity in actuator response relationship from input to output obtaining results from the fact that the frequency characteristics of the UAV actuator stabilization are non-standard. The frequency characteristics being non-standard were described using the database formed by means of experimental data. The frequency characteristics were laid into the frequency model of UAV stabilization system to estimate the stability margin using the classic frequency methods. These peculiarities significantly hindered the modelling and UAV stabilization system analyses for UAV actual tests.

The experimental frequency response was obtained sending the harmonic signals from the generator onto the actuator model input. The harmonic signals were adherent to the control amplitude $U_{input}(t)$ with the frequency range 1÷200 Hz (with the step of 1 Hz). The servoing signal was fixed by the feedback potentiometer – the angular position transducer of the drive electromechanical unit output arm. Continuous control and servoing were sent as database using the analog to digital converter with the sampling frequency 4000 Hz. The database was sent to the personal computer, which calculated the actuator drive model frequency characteristics using the discrete Fourier transformation. The nonlinear frequency response was obtained similarly - using discrete Fourier transformation for the functions $U_{input}(t)$ and $U_{output}(t)$.

The comparison of frequency response for nonlinear drive model (L3_model, phase3_model) and the experiment results for the drive model (L3_exp, phase3_exp) for the mode of small input signals ($U_{input}(t) = 3^\circ$) is shown in Figure 2.

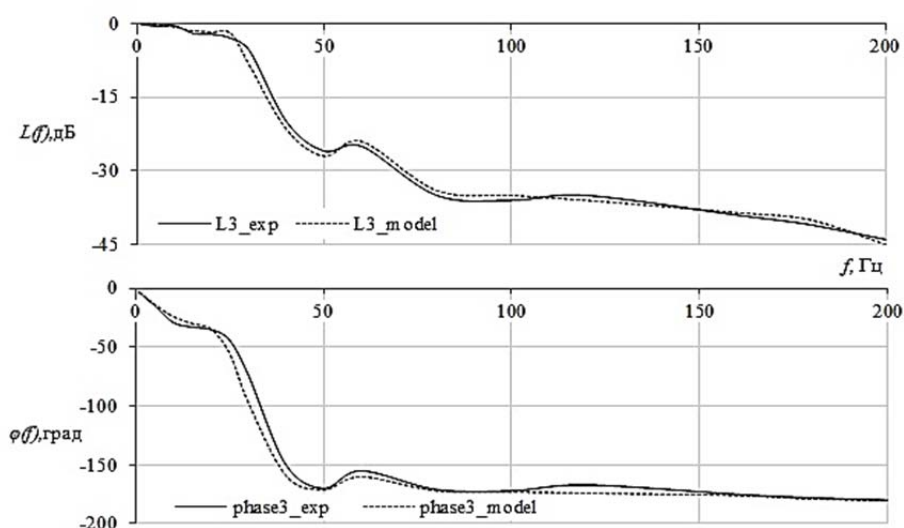


Fig. 2. Comparison of the frequency response of the drive prototype with frequency response of the nonlinear model

It is worth mentioning that the given abrupt inhibition of the amplitude-response curve at frequencies exceeding 30 Hz is explained by the clock domain of the first-bending frequency of the UAV body. (39÷50 Hz).

The small control signal servoing mode ($0,5^\circ \div 3^\circ$) does not provide the electric drive characteristics using the linear regulators. The shown frequency response characteristics are obtained using the digital regulator which implements the nonlinear algorithms with the master model when paired with combined control for the control signal.

Within the frequency range below 20 Hz the regulator structure is almost linear: during the control signal servoing the system follows the master model quite accurately. At the same time, for the frequency range above 20 Hz with the given abrupt frequency response inhibition, the system becomes ineffective. It is worth mentioning that the use of combined control increases the pass band for the small input signals below 70-100 Hz, which can impact the drive interference immunity and the “steer-drive” system stability for the control surface flexural-torsional instability range.

In order to provide the required frequency response in the frequency band outside the band pass (with the UAV body flexural mode frequency range being most important) the digital controller uses the algorithms of changing the forward-path gain depending on the input signal frequency [12], which is being estimated using the structure shown in Figure 3.

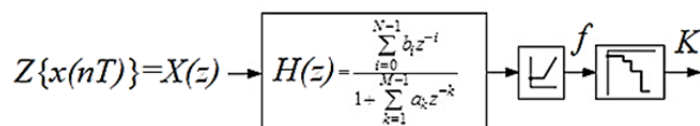


Fig. 3. The generation organization of the gain compensation

Figure 3 shows: $Z\{x(nT)\}=X(z)$ – the discrete input signal from the controller analog to digital converter; $H(z)$ – response relationship of a part of controller algorithms for the input signal frequency estimation; a_k, b_i, M, N – the coefficients and parameters of z - response relationship $H(z)$, f – the frequency evaluation signal; K – the controller gain signal.

The main essential nonlinearity of this structure is the nonlinear property K , aimed at the controller gain reduction at frequencies exceeding 20Hz. The introduction of this structure allows to form the required frequency response inhibition above 30 Hz. It is the significantly nonlinear K that results in difficulty of the controller frequency band description.

Another considerable feature of the nonlinear systems is the change of frequency response at different input amplitudes; thus, the frequency description should be introduced for strictly predetermined range which is critical for the research. For this case the critical input amplitudes are within the range of $0,5^\circ \div 3^\circ$, which characterizes the main UAV actuator modes in flight.

As the experimental frequency response characteristics show in Figure 2, for the small input signal processing ($0,5^\circ \div 3^\circ$), the band pass for the level -3 dB is 20 Hz, and the phase lag for the band pass $\approx 40^\circ \div 45^\circ$. This frequency characteristics is typical for the first-order block:

$$W(p) = \frac{1}{Tp+1}; T = \frac{1}{2\pi f} = \frac{1}{2\pi \cdot 20 \Gamma_u} = 0,00796.$$

For the higher frequencies the frequency response is inhibited abruptly and the phase lag becomes significant. The oscillatory link has the closer approximation to such frequency behavior which provides log-magnitude and phase diagram slope -40 dB/decade for frequencies above the band pass. It is easy to notice that at frequencies above 20 Hz (band pass) the frequency response of nonlinear model and experimental characteristics have a much steeper log-magnitude and phase diagram slope (approximately -80 dB/decade), accordingly, the given slant range will require at least two, connected in sequence second order blocks, i.e. the system of at least fourth order. As all the typical inertial lags are minimum phase in character, the second order block within the band pass has the lag of approximately -90° , and the fourth-order system has the lag of -180° . It becomes obvious that within the minimum-phase typical lag it is im-

possible to implement the system which has the frequency response adequate to the fourth-order system, keeping the phase lag within the band pass the same as that of the first-order block.

At present the question of nonminimal phase system application for the dynamic characteristics description remains disputable. Meanwhile, there exists a definition that states that the system characteristics is a function that shows the system feedback to the impact. This definition is chosen as the elementary [13] for the solution of the problem. The system feedback depends on the impact and the properties of the system itself. As follows, let us consider the Fourier integral and the Duhamel integral:

$$y(t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} K(\omega) S_x(\omega) e^{-j\omega t} d\omega,$$

$$y(t) = \int_0^t x'(\tau) h(t - \tau) d\tau.$$

In the Fourier integral the impact is shown using spectrum $S_x(\omega)$, and in the Duhamel integral via the function $x(t)$ itself. In the Fourier integral the system properties are expressed via the transition factor $K(\omega)$, which is a transfer function plot, in the Duhamel integral – via the function $h(t)$, which is a time response characteristic. As we can see, the system properties can be described in a number of different ways: different characteristics can be applied, as every characteristic expresses the system properties from the certain, convenient and natural for these circumstances point of view [13]. In our case we have the characteristics of the working drive prototype and its mathematical time domain formulation as a complete nonlinear model, i.e. we have a physically implemented system, which possesses strictly predetermined properties. Considering this, the research of the drive operation within a time domain and its time response characteristics should be carried out by means of its complete nonlinear model, comparing the modelling results to the results of the experiment. Therefore, the steering drive frequency model must be implemented in a convenient form, which is necessary to be contained within the stabilization system frequency model to evaluate the gain margin using the descriptive and tried-and-true frequency tools. Thus, we shall further consider the given steering drive dynamic properties only in the frequency area.

Frequency response function $W(j\omega)$ is the Fourier figure for its impulse response $w(t)$ and is expressed using the integral transformation:

$$W(j\omega) = \int_0^{\infty} w(t) e^{-j\omega t} dt = A(\omega) e^{j\psi} = U(\omega) + jV(\omega),$$

where $A(\omega)$ – frequency response function block, $\psi(\omega)$ – the functional argument or the phase, $U(\omega)$ and $V(\omega)$ – the real-definite and imaginary frequency response function components [14].

As it has already been mentioned, we have a physically implemented system with the frequency characteristics obtained experimentally which match the modelling results from the complete time response nonlinear model (fig. 2). The important feature of Fourier transformation is the fact that it is applicable only for the steady modes. The system frequency response presents a complex plane vector tip geometric locus (hodograph diagram) of the frequency response function $W(j\omega) = U(\omega) + jV(\omega)$ at changing of the frequency from zero ad infinitum. As follows, if the frequency response function of the nonminimum phase system matches the experimental characteristics well, mathematically, the frequency model obtained will show the frequency properties of the real system for the steady modes with the control input harmonic signals with a certain amplitude. As it was mentioned above, the main mode of the drive is considered to be the control signal frequency band within $0,5^\circ \div 3^\circ$.

The graphical approach is used to find the frequency model parameters due to its ostensiveness. The drive frequency response shows that the amplitude component inhibition starts in the frequency

band close to 20 Hz, and the transition factor is approaching 1. Accordingly, the constants of time will match these frequencies and will fit the range of 0.006-0.008 s.

Consequently, the first block of the second order must prove a well-defined resonance peak for the frequency band 20 Hz ($\xi < 0.5$). The second block of the second order must compensate the oscillability of the first one by means of a higher response time and less transition factor. The derivative unit in the negative feedback must compensate the significant phase lag, amplification coefficient must determine the final frequency response value to the level of -3 dB. By combining the blocks, the negative feedbacks and the parameter varying, the frequency model transfer factor was obtained and it approaches the frequency properties of the electric drive in question:

$$W_{\text{пр}}(p) = k \cdot w1(p) \cdot \frac{w2(p)}{w2(p) - w3(p)},$$

$$w1(p) = \frac{k1}{T_1^2 p^2 + 2T_1 \xi p + 1}, \quad k1 = 0.99, \quad T_1 = 0.0063516, \quad \xi = 0.2075;$$

$$w2(p) = \frac{k2}{T_2^2 p^2 + T_3 p + 1}, \quad k2 = 0.15, \quad T_2 = 2.601 \cdot 10^{-5}, \quad T_3 = 0.663;$$

$$w3(p) = T_4 p, \quad T_4 = 1.5915 \cdot 10^{-5}; \quad k = 0.91.$$

The frequency response within the band pass and the frequency band of the UAV body first-bending frequency, obtained using the given frequency model (L_freq_model, Phase_freq_model), is shown in Figure 4.

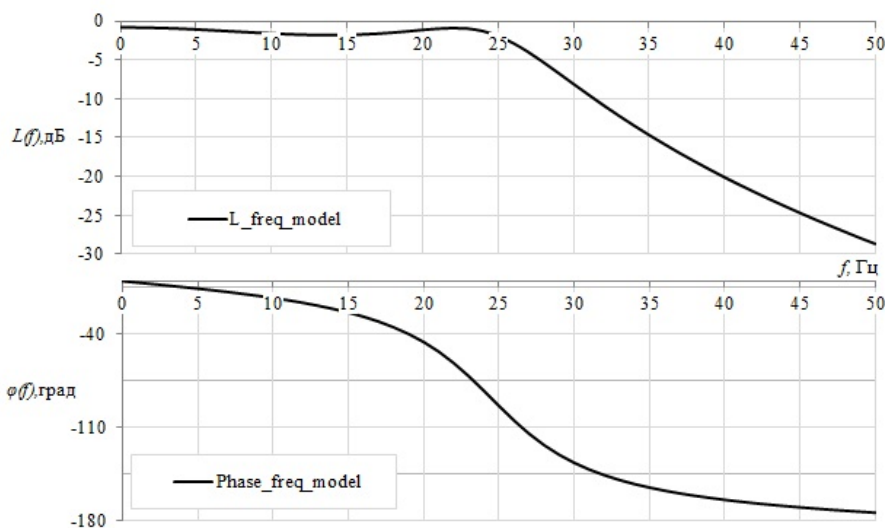


Fig. 4. The frequency response of the drive frequency model

In order to obtain the digital controller frequency model z -response relationship let us apply the Tustin's method transformation (bilinear transformation) [15]:

$$p \approx \frac{2}{T_s} \frac{z-1}{z+1}.$$

In order to form the structure of the control signal which is sent to the steer drive actuator input, the system uses the controller 1887BE1, with the stroking frequency 7,3728 MHz, and the sampling frequency 1000Hz ($T_s=0,001s$). At the given value $T_s=0,001s$ we will obtain the digital controller frequency model z -response relationship:

$$W_{pn}(z) = k \cdot w1(p) \cdot \frac{w2(p)}{w2(p) - w3(p)} \Bigg|_{p \rightarrow \frac{2}{T_s} \frac{z-1}{z+1}} = k \cdot w1(z) \cdot \frac{w2(z)}{w2(z) - w3(z)},$$

$$w1(z) = \frac{k1}{T_1^2 \left(\frac{2}{T_s} \frac{z-1}{z+1} \right)^2 + 2T_1 \xi \left(\frac{2}{T_s} \frac{z-1}{z+1} \right) + 1}, \quad k1 = 0.99, \quad T_1 = 0.0063516, \quad \xi = 0.2075;$$

$$w2(z) = \frac{k2}{T_2^2 \left(\frac{2}{T_s} \frac{z-1}{z+1} \right)^2 + T_3 \left(\frac{2}{T_s} \frac{z-1}{z+1} \right) + 1}, \quad k2 = 0.15, \quad T_2 = 2.601 \cdot 10^{-5}, \quad T_3 = 0.663;$$

$$w3(z) = T_4 \left(\frac{2}{T_s} \frac{z-1}{z+1} \right), \quad T_4 = 1.5915 \cdot 10^{-5}; \quad T_s = 0.001; \quad k = 0.91.$$

Using the known relators $z = e^{j\omega T_s} = e^{j2\pi f T_s} = \cos(2\pi f T_s) + j \cdot \sin(2\pi f T_s)$, we will obtain the frequency range description of the digital system and will equal the frequency response from the continuous frequency model (L_analog, Phase_analog) with the frequency response z -response relationship of the digital controller frequency model (L_digital, Phase_digital). The comparison of the given frequency responses is shown in Figure 5.

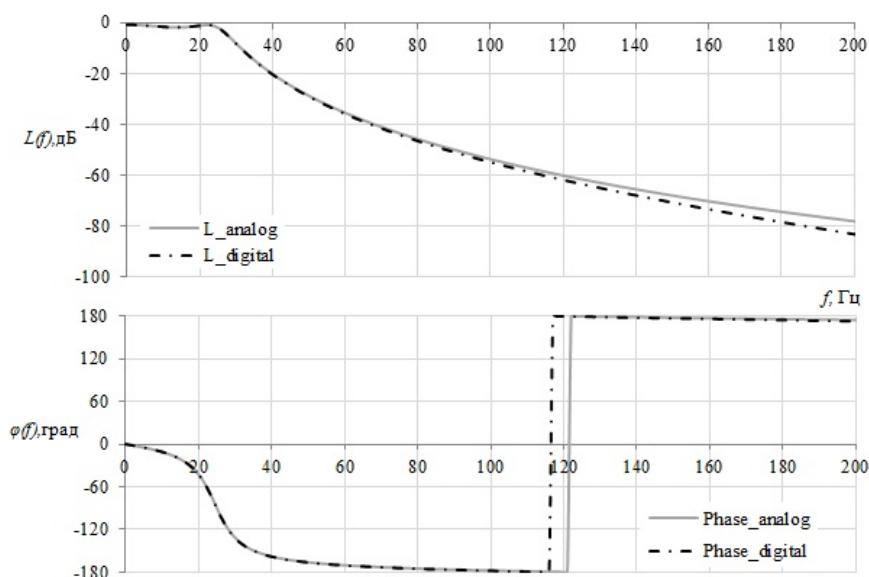


Fig. 5. Comparison of the frequency responses of the analog and digital frequency models

Figure 5 shows that the classic way of obtaining the digital system applying the bilinear transformation using its analogue prototype does not provide amplitude and phase distortions into the frequency characteristics within the drive band pass and within the UAV body first-bending frequency. As for the higher bending frequencies of the UAV body, the frequency response inhibition for the analogue and digital systems matches the experimental characteristics shown in Figure 2 quite well. Ac-

cordingly, the obtained steering drive description in the frequency band has a rather convenient for use within the UAV stabilization system frequency model.

RESULTS AND DISCUSSION

To estimate the frequency response adequacy to the acting prototype characteristics, let us compare the modelling results for the complete non-linear real time model ($L_real_time_model$, $Phase_real_time_model$) and the experimental frequency response ($L_real_actuator$, $Phase_real_actuator$) shown in Figure 6.

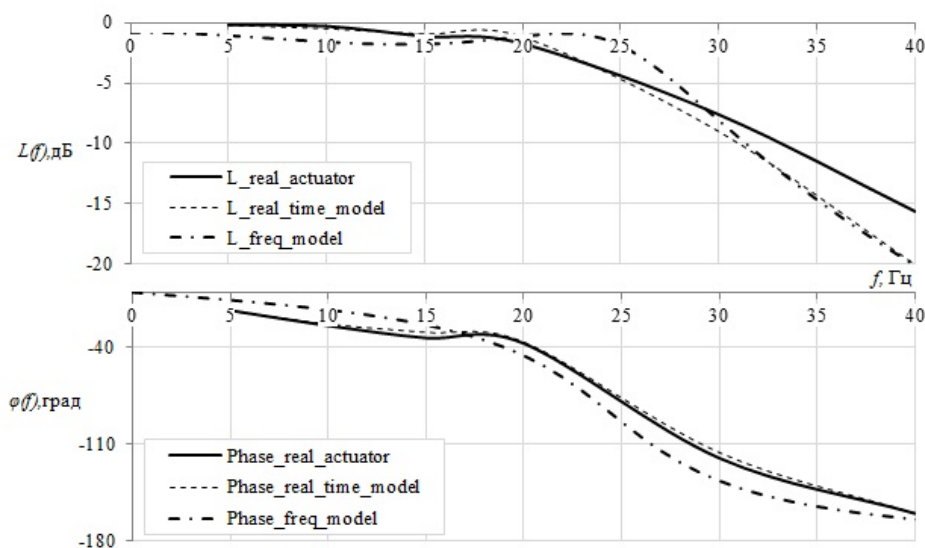


Fig. 6. Comparison of the frequency responses

The comparison of the frequency responses shown in Figures 2 and 5÷6, demonstrates that the results obtained from the nonlinear real-time model have a good convergence with the frequency response results obtained from the acting prototype.

Consequently, the given way of the considerably nonlinear drive with a digital controller description using the nonminimum phase system in the frequency area is quite informative as for the sake of gain margin evaluation within the UAV stabilization system frequency model.

CONCLUSION

The research process for the maneuverable UAV stabilization system gain margin considered the problem of significantly nonlinear drive with a digital controller dynamic characteristics description. For linear nonminimum phase structures the solution of such problems is quite challenging, as for the systems with three or more nonlinearities there are very few adequate methods in the frequency area.

As the application of nonminimum phase systems supposes their physical implementation, the physically implemented system was considered, and the research object was the drive acting prototype, which possessed strictly predetermined properties. The frequency characteristics were obtained experimentally and have a good convergence with the modelling results, obtained from the full real-time model. As a result of the research, the frequency response description was suggested with substantially nonlinear algorithms of the digital controller using the nonminimum phase system which has the important feature of amplitude frequency response and phase-frequency independence. The computed results obtained from the given drive frequency model have a good convergence with the experimental

frequency response data from the acting drive prototype and the results obtained from the drive complete nonlinear model.

The main advantage the suggested frequency model is its simple and convenient form that is applicable to be used as a component of the UAV stabilization system frequency model. Also, it is necessary to mention that the frequency model was implemented in two variants: as the response relationship of the continuous system and as z-response relationship of the initial analogue prototype, which allows to estimate the stability of both continuous and digital UAV stabilization systems using reputable classic frequency methods.

REFERENCES

1. **Mizrokhi, V.Ya.** (2010). *Proyektirovaniye upravleniya zenitnykh raket* [Control design of anti-aircraft missiles. Educational and scientific edition]. Moscow: Izdatelstvo «Ekslibris-Press», 252 p. (in Russian)
2. **Karkle, P.G. and Smyslov, V.I.** (2017). *Modalnyye ispytaniya letatelnykh apparatov i vosproizvedeniye silovykh vozhdeystviy* [Aircraft modal testing and the reproduction of force impacts]. Moscow: Tekhnosfera, 155 p. (in Russian)
3. **Parafes, S.G. and Smyslov, V.I.** (2013). *Metody i sredstva obespecheniya aerouprugoy ustoychivosti bespilotnykh letatelnykh apparatov* [Methods and means of aeroelastic stability of unmanned aerial vehicles]. Moscow: Izdatelstvo MAI, 176 p. (in Russian)
4. **Parafes, S.G. and Turkin, I.K.** (2016). *Aktualnyye zadachi aerouprugosti i dinamiki konstruktivnykh vysokomanevrennykh bespilotnykh letatelnykh apparatov* [Actual problems of aeroelasticity and dynamics of highly maneuverable unmanned aerial vehicles structures]. Moscow: Izdatelstvo MAI, 183 p. (in Russian)
5. **Akimov, V.N., Ulasevich, V.P. and Gryzin, S.V.** (2017). *Different types comparison of flight control actuators for medium range sam.* Journal “Aerospace Defense Herald”, no. 4 (16), pp. 23–28. (in Russian)
6. **Petrov, B.I., Polkovnikov, V.A. and Rabinovich, L.V.** (1982). *Dinamika sledyashchikh privodov: Uchebnoe posobiye dlya tekhnicheskikh VUZov* [Tracking actuators dynamics: Training manual for Technical Universities], in Rabinovich L.V. (ed.). 2nd ed., revised and added. Moscow: Mashinostroyeniye, 496 p. (in Russian)
7. **Krymov, B.G., Rabinovich, L.V. and Stebletsov, V.G.** (1987). *Iсполнительные устройства систем управления летательными аппаратами* [Actuators for aircraft control systems]. Moscow: Mashinostroyeniye, 262 p. (in Russian)
8. **Bliznova, T.B., Karev, V.I., Obolenskiy, Yu.G., Polkovnikov, V.A. and Samsonovich, S.L.** (2009). *Method and calculation of basic parameters of different types of control servoactuators using minimal installed power criterion.* Journal of Computer and Systems Sciences International, vol. 48, no. 5, pp. 788–800. DOI: 10.1134/S106423070905013X. (in Russian)
9. **Parafes, S.G., Ivanov, D.N. and Oparin, A.S.** (2016). *Model of stability study of rudder actuator system of maneuverable unmanned aerial vehicle.* Civil Aviation High Technologies, no. 225 (3), pp. 143–150. (in Russian)
10. **Serebryakov, A.N. and Korobotov, D.V.** (2005). *Neminimalno-fazovaya korrektsiya tsifrovogo elektroprivoda* [Non-minimum phase correction of a digital electric drive]. Bulletin of South Ural State University. Series: Power Engineering, no. 9 (49), pp. 92–96. (in Russian)
11. **Semenov, A.V. and Gayduk, A.R.** (2012). *Synthesis of discrete nonminimum-phase tracking loop system.* Izvestiya SFedU. Engineering Sciences, no. 2 (127), pp. 53–59. (in Russian)
12. **Popov, A.I. and Goncharov, A.S.** (2011). *Adaptivnaya sistema pryamogo tsifrovogo upravleniya sledyashchego rulevogo elektroprivoda avtonomnykh obektov* [Adaptive system of direct digital control of the tracking actuators of autonomous objects]. Elektrotekhnicheskiye komplekсы i sistemy upravleniya, no. 1, pp. 37–41. (in Russian)

13. Kharkevich, A.A. (2007). *Osnovy radiotekhniki* [Fundamentals of radio engineering]. 3rd ed., ster., Moscow: FIZMATLIT, 512 p. (in Russian)
14. Besekerskiy, V.A. and Popov, Ye.P. (1972). *Teoriya sistem avtomaticheskogo regulirovaniya* [Theory of automatic control systems]. 2nd ed. Moscow: Nauka, 768 p. (in Russian)
15. Isermann, R. (1981). *Digital control systems*. Springer-Verlag, Berlin, Heidelberg, 566 p. DOI:10.1007/978-3-662-02319-8

INFORMATION ABOUT THE AUTHOR

Sergey V. Gryzin, Design Engineer of Dolgoprudny Research and Production Enterprise, Postgraduate Student of the Design and Strength of Aircraft, Rocket and Space Products Chair, Moscow Aviation Institute (National Research University), gryzzin@mail.ru.

ЧАСТОТНАЯ МОДЕЛЬ СУЩЕСТВЕННО НЕЛИНЕЙНОГО РУЛЕВОГО ПРИВОДА С ЦИФРОВЫМ МИКРОКОНТРОЛЛЕРНЫМ РЕГУЛЯТОРОМ

С.В. Грызин^{1,2}

¹ Долгопрудненское научно-производственное предприятие, г. Долгопрудный, Россия

² Московский авиационный институт (национальный исследовательский университет), г. Москва, Россия

При проектировании системы стабилизации высокоманевренных беспилотных летательных аппаратов (БЛА) одной из актуальных задач является исследование функционирования рулевого привода в полосе частот, соответствующей изгибным колебаниям корпуса БЛА. Для обеспечения устойчивости системы стабилизации БЛА к динамическим характеристикам привода могут предъявляться достаточно противоречивые требования. В частности, требование к резкому подавлению амплитудно-частотной характеристики на частоте изгибных колебаний БЛА при минимальных фазовых искажениях в полосе частот управления продольного и боковых каналов системы стабилизации может существенно усложнить задачу исследования устойчивости системы управления движением БЛА. В статье рассматривается действующий макет электропривода с цифровым микроконтроллерным регулятором, предназначенный для использования на высокоманевренном БЛА. Адаптивные алгоритмы цифрового регулятора позволяют обеспечить необходимые фазовые запаздывания в полосе частот управления и при этом почти полное подавление гармонических составляющих сигналов управления на частотах изгибных колебаний корпуса БЛА. Используемые алгоритмы имеют существенно нелинейный характер и основаны на изменении коэффициента усиления прямой цепи контура привода в зависимости от частоты входного сигнала, что значительно усложняет получение передаточной функции рулевого привода для использования в частотной модели системы стабилизации. Обычно рулевой привод описывается линейной минимально-фазовой системой, представленной в виде передаточной функции одного из типовых звеньев первого или второго порядков, но для указанного рулевого привода с заданными динамическими характеристиками подобный подход оказывается несостоятельным. В результате исследования предложен способ получения частотной модели рулевого привода, которая реализована в виде неминимально-фазовой системы, основным свойством которой является независимость амплитудно-частотной и фазо-частотной характеристик. В процессе исследований проведено сравнение результатов, полученных на предложенной модели с результатами экспериментов на макете электропривода и его полной нелинейной временной модели. Главным преимуществом предложенной частотной модели является достаточно простое описание рулевого привода в частотной области, удобное для использования в составе частотной модели системы стабилизации при исследовании задач обеспечения устойчивости полета БЛА.

Ключевые слова: беспилотный летательный аппарат (БЛА), система стабилизации, электропривод, частотные характеристики, цифровой микроконтроллерный регулятор, неминимально-фазовые системы, частотная модель, нелинейная модель.

СПИСОК ЛИТЕРАТУРЫ

1. Мизрохи В.Я. Проектирование управления зенитных ракет: учеб.-науч. издание. М.: Издательство ООО «Экслибрис-Пресс», 2010. 252 с.

2. Карклэ П.Г., Смыслов В.И. Модальные испытания летательных аппаратов и воспроизведение силовых воздействий. М.: Техносфера, 2017. 155 с.
3. Парафесь С.Г., Смыслов В.И. Методы и средства обеспечения аэроупругой устойчивости беспилотных летательных аппаратов. М.: Изд-во МАИ, 2013. 176 с.
4. Парафесь С.Г., Туркин И.К. Актуальные задачи аэроупругости и динамики конструкций высокоманевренных беспилотных летательных аппаратов. М.: Изд-во МАИ, 2016. 183 с.
5. Акимов В.Н., Уласевич В.П., Грызин С.В. Сравнение различных типов рулевых приводов для ЗУР средней дальности // Вестник воздушно-космической обороны. 2017. № 4 (16). С. 23–28.
6. Петров Б.И. Динамика следящих приводов: учебное пособие для втузов / Б.И. Петров, В.А. Полковников, Л.В. Рабинович и др. / Под ред. Л.В. Рабиновича. 2-е изд., перераб. и доп. М.: Машиностроение, 1982. 496 с.
7. Крымов Б.Г., Рабинович Л.В., Стеблецов В.Г. Исполнительные устройства систем управления летательными аппаратами. М.: Машиностроение, 1987. 262 с.
8. Близнова Т.Б. Разработка методики и расчет основных параметров рулевых приводов различных типов по критерию минимальной установленной мощности / Т.Б. Близнова, В.П. Караев, Ю.Г. Оболенский, В.А. Полковников, С.Л. Самсонович // Известия Российской академии наук. Теория и системы управления. 2009. № 5. С. 118–130.
9. Парафесь С.Г., Иванов Д.Н., Опарин А.С. Модель исследования устойчивости системы «руль – привод» маневренного беспилотного летательного аппарата // Научный Вестник МГТУ ГА. 2016. № 225 (3). С. 143–150.
10. Серебряков А.Н., Коробатов Д.В. Неминимально-фазовая коррекция цифрового электропривода // Вестник ЮУрГУ. Серия «Энергетика». 2005. № 9 (49). С. 92–96.
11. Семенов А.В., Гайдук А.Р. Синтез дискретных неминимально-фазовых следящих систем // Известия ЮФУ. Технические науки. 2012. № 2 (127). С. 53–59.
12. Попов А.И., Гончаров А.С. Адаптивная система прямого цифрового управления следящего рулевого электропривода автономных объектов // Электротехнические комплексы и системы управления. 2011. № 1. С. 37–41.
13. Харкевич А.А. Основы радиотехники. 3-е изд. стер. М.: ФИЗМАТЛИТ, 2007. 512 с.
14. Бесекерский В.А., Попов Е.П. Теория систем автоматического регулирования. 2-е изд. М.: Наука, 1972. 768 с.
15. Изерман Р. Цифровые системы управления: пер. с англ. / Под ред. чл.-корр. АН СССР И.М. Макарова. М.: Мир, 1984. 541 с. Перевод изд.: Rolf Isermann. Digital Control Systems. Berlin: Springer-Verlag. New York: Heidelberg. 1981.

СВЕДЕНИЯ ОБ АВТОРЕ

Грызин Сергей Владимирович, инженер-конструктор Долгопрудненского научно-производственного предприятия, аспирант кафедры проектирования и прочности авиационно-ракетных и космических изделий Московского авиационного института (национального исследовательского университета), gryzzin@mail.ru.

Поступила в редакцию
Принята в печать

09.02.2020
21.05.2020

Received
Accepted for publication

09.02.2020
21.05.2020