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Control Technologies and Instrumentation in Aerospace Engineering

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Abstract: The paper is devoted to the Russian system of personnel training for the aerospace industry and design bureaus describing. The structure of aerospace specialties and universities in Russia are analyzing. Changes in aerospace education since the first IFAC Congress in Moscow are discussing. The specific methods in the design of flight control systems, aerospace navigation systems and systems for measuring the flight parameters are shown. The original methodology for the control systems study in the frequency domain is described.

Keywords: flight control systems, aerospace education, aerospace specialties, the control systems study

1. INTRODUCTION

Russia has been a recognized space power since October 4, 1957, when the world's first artificial satellite was launched. This title was confirmed on April 12, 1961, when Yuri Gagarin made the world's first manned space flight. Both events became possible as a result of the development and creation of the legendary R7 rocket under the leadership of General designer Sergey Pavlovich Korolev.

The second event was more expected in the world than the first, because much of the state and level of research and technical education in the USSR was cleared up at the First world Congress of IFAC, held in June-July 1960 in Moscow. The number of reports at the Congress from the USSR was the first and more than from the United States.

Interest in the country that launched the first satellite was huge and extended not only to scientific results, but also to the structure of scientific and engineering centers and the system of technological, physical and mathematical education. Much has changed since that time. In 1991 the USSR collapsed. For another 20 years, Russia tried to copy the Western way of development in everything, abandoning its former Soviet even positive experience. The two-level (bachelor-master) Bologna system has been adopted in education, and even now this decision still causes a lot of controversy, and for some particularly important aerospace engineering specialties, as a result, a single-stage curriculum for training specialists has been preserved. The Ministry of defense of the Russian Federation in principle does not recognize the bachelor's degree and subordinate military universities do not consider it possible to prepare demanded by someone specialists during 4 years.

The transition to a three-level system of education with the introduction of the higher title of doctor of philosophy has not yet been implemented, preserved the degree of candidate of sciences and a completely unique degree of doctor of sciences. The process of transformation in science and higher education will obviously continue, but more cautiously. It is headed by the new Ministry of science and higher education established in mid-2018 under the leadership of Mikhail Kotyukov. The Ministry is now directly in charge of the Russian Academy of Sciences.

It is difficult to describe and analysis any system under transformation. But we will try to do it in relation to the problem of development and study of methods of automatic control in aerospace engineering education.

2. RUSSIAN AEROSPACE UNIVERSITIES

The list of Russian universities teaching aerospace students is shown below. It contains 23 state universities in 15 cities, including 5 universities in Moscow and 4 universities in St. Petersburg. We would like to highlight the St. Petersburg state University of aerospace instrumentation, where I work – the only University in the world with the name dedicated to aerospace instrumentation. The reason is simple - it is in St. Petersburg many research institutes and design bureaus of this profile are concentrated, developing navigation and flight control systems for aviation and, to a lesser extent, for cosmonautics. Note also located in St. Petersburg military space Academy named after A. F. Mozhaisky, which trains specialists for all Russian spaceports.

The list of Russian universities, where there are faculties for training in aerospace engineering specialties:

1) Baltic State Technical University "Voenmech" named after D.F. Ustinov;
2) Bauman Moscow State Technical University;
3) Irkutsk State Technical University;
4) Kazan Aviation Institute;
5) Komsomolsk-on-Amur State Technical University;
6) Moscow Aviation Institute;
7) Moscow Institute of Physics and Technology;
8) Moscow State Technical University of Civil Aviation (MSTUCA);
9) Mozhaysky Military Space Academy;
10) Novosibirsk State Technical University;
11) Omsk State Technical University;

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12) Perm National Research Polytechnic University;
13) Rybinsk State Aviation Technical University;
14) **Saint Petersburg State University of Aerospace Instrumentation;**
15) Saint Petersburg State University of Civil Aviation;
16) Samara State Aerospace University;
17) Siberian State Aerospace University;
18) Skolkovo Institute of Science and Technology (Skoltech);
19) South Ural State University;
20) Ufa State Aviation Technical University;
21) Voronezh Aviation Engineering University.

More than half of these universities are universities of a wide profile, in which only a small proportion of students specialize in aerospace engineering with enhanced study of special disciplines. Their classification as aerospace universities is very conditional, especially in the conditions of reducing the production of civil aircraft in Russia and reducing the need for appropriate specialists. The policy of the state is to strengthen support only "leading" universities that claim high places in the world rankings. These include usually "capital" universities, as well as universities in cities that have powerful aircraft or space production enterprises. Therefore, we will consider only 11 fully aerospace universities, the list of which is given below.

Narrow list of leading Russian aerospace universities:

1) Baltic State Technical University "Voenmech" named after D.F. Ustinov;
2) Bauman Moscow State Technical University;
3) Kazan Aviation Institute;
4) Moscow Aviation Institute;
5) Moscow Institute of Physics and Technology;
6) Mozhaysky Military Space Academy;
7) Saint Petersburg State University of Aerospace Instrumentation;
8) Samara State Aerospace University;
9) Siberian State Aerospace University;
10) Ufa State Aviation Technical University;
11) Voronezh Aviation Engineering University.

3. TYPICAL SETS OF AEROSPACE SPECIALTIES IN RUSSIAN UNIVERSITIES

A set of officially accredited aerospace specialties in Russia is very large, and their number in Russia is greater than in most other "aerospace" countries. Accordingly, training in each of these specialties is more profound. All curricula include general scientific, general technical and special training with approximately the same distribution of training hours between these three areas. Such an extremely broad name as aerospace technologies is generally absent among the accredited specialties of higher education in Russia.

Some aerospace specialties that SUAI teaches with license are givern below. They are related to aerospace instrumentation.

1) Traffic control systems and navigation;
2) Technical operation of aviation electrical systems and flight-navigation complexes;
3) Technical operation of aircraft and engines;
4) Technology of transport processes;
5) Instrumentation;
6) Computer Science and Engineering;
7) System analysis and management;
8) Aircraft control systems;
9) Laser technology;
10) Radio electronic systems and complexes;
11) Radio engineering;
12) Infocommunication technologies and communication systems;
13) Optotechnics;
14) Technical operation of transport radio equipment;
15) Design and technology of electronic means;
16) Computer Science and Engineering;
17) Applied Informatics;
18) Software Engineering;
19) Applied Mathematics and Computer Science;
20) Software and administration of information systems;
21) Electronics and Nanoelectronics;
22) Information systems and technologies;
23) Information security of automated systems;
24) Information Security.

A wider range of space specialties is presented in the list below [Mozhaysky Military Space Academy, 2019].

1) Design, production and operation of rockets and rocket-space complexes;
2) Navigation and ballistic support of space technology applications;
3) Application and operation of automated systems for special purposes;
4) Aircraft control systems;
5) Special organizational and technical systems;
6) Radio electronic systems and complexes;
7) Special radio systems;
8) Infocommunication technologies and special communication systems;
9) Heat and power supply of special technical systems and objects;
10) Special life support systems;
11) Meteorology of special purpose;
12) Special radio systems;
13) Electronic and opto-electronic devices and systems for special purposes;
14) Application and operation of automated systems for special purposes;
15) Computer security;
16) Information and analytical security systems;
17) Military cartography.
18) Metrological provision of weapons and military equipment.

4. SOME OF THE LEADING AEROSPACE ORGANIZATIONS ASSOCIATED WITH NAVIGATION AND FLIGHT CONTROL, WHERE GRADUATES OF AEROSPACE UNIVERSITIES WORK

1) SRI of aviation systems «GOSNIIAS» is a scientific center for system studies of military and civil aviation, development of algorithms, information and software for the functioning of aviation systems and analysis of the effectiveness of aviation systems;
2) JSC "RSI of Aviation Equipment";
3) Keldysh Institute of Applied Mathematics of RAS, Moscow;
4) Khrunichev State Research and Production Space Center www.khrunichev.ru;
5) RSC "Energia", Korolev www.enegia.ru;
6) SPC "Progress", Samara www.samspace.ru ;
7) Center for Operation of Space Groung Based Infrastructure "TsENKI" www.en.russian.space;
8) Lavochkin Assotiation, www.laspace.ru;
9) JSC MIC "NPO Mashinostroyenia" www.npomash.ru;
10) JSC Central research and production Association «Leninets» (St. Petersburg) - the largest producer of a wide range of high quality electronics systems;
11) JSC Concern «Almaz-Antey» is one of the largest holdings of the military-industrial complex of Russia which includes more than 50 research and production associations, research institutes, design bureaus and plants. Five leading enterprises of the Concern operate in St. Petersburg.

The Northwest regional center will unite the following industrial enterprises in one territory:

12) JSC «All-Russian Scientific and Research Institute of Radio Equipment» ;
1) JSC «Russian Institute of radio navigation and time» (RIRT).

5. WORKING PROGRAMS FOR THE STUDY OF METHODS AND CONTROL SYSTEMS IN AEROSPACE ENGINEERING

Unlike training for other engineering specialties, aerospace specialties involve the study of methods and control systems within the framework of two disciplines: “Theory of automatic control” and “Systems of automatic control of flight". The first course provides knowledge of the theory of control in the framework of General technical training, the second – a more targeted system of direction of aircraft, taking into account the specifics of aircraft, helicopters, unmanned aerial vehicles, missiles, satellites, and spacecraft. The working program on the "Theory of automatic control" operating in the SUAI is given below in a partly abbreviated form.

Section I. General Information On Automatic Control Systems

Chapter 1. Types of automatic control systems
Chapter 2. Programs and laws of regulation. Adaptive systems

Section II. Ordinary Linear Automatic Regulation Systems

Chapter 3. Linearization of differential equations of automatic control systems
Chapter 4. Dynamic links and their characteristics
Chapter 5. Drawing up the initial differential equations of automatic control systems
Chapter 6. Sustainability Criteria
§ 6.1. The concept of sustainability regulatory systems
§ 6.2. Hurwitz Sustainability Criterion
§ 6.3. Mikhailov's stability criterion
§ 6.4. Nyquist sustainability criterion
§ 6.5. Determination of stability by logarithmic frequency characteristics
Chapter 7. Construction of the transition curve in automatic control systems
§ 7.1. General considerations
§ 7.2. Direct solution of the original differential equation
§ 7.3. Reduction of a non-homogeneous equation to a homogeneous
§ 7.4. Using Fourier, Laplace and Carson-Heaviside Transforms
Chapter 8. Regulatory quality assessment
§ 8.1. General considerations
§ 8.2. Accuracy in typical modes
§ 8.3. Error rates
§ 8.4. Determination of the stability and performance of the transition characteristic
§ 8.5. Approximate assessment of the type of the transition process on the real frequency response
§ 8.6. Root methods
§ 8.7. Vyshnegradsky diagram
§ 8.8. Integral estimates
§ 8.9. Frequency quality criteria
§ 8.10. Regulatory Sensitivity
Chapter 9. Improving the accuracy of automatic control systems
§ 9.1. General methods
§ 9.2. Invariance theory and combined control
§ 9.3. Non-unit feedbacks
Chapter 10. Improving the quality of the regulatory process
§ 10.1. About corrective means
§ 10.2. Successive corrective links
§ 10.3. Parallel corrective links
§ 10.4. Feedback
Chapter 11. Random processes in automatic control systems
§ 11.1. Stationary random processes
§ 11.2. Correlation function
§ 11.3. Spectral density of stationary processes
§ 11.4. Passing a random signal through a linear system
§ 11.5. Calculation of steady-state errors in the automatic system
§ 11.6. Calculations for the minimum mean-square error
Chapter 12. Methods of synthesis of automatic control systems
§ 12.1. Root method
§ 12.2. Standard Transition Method
§ 12.3. Logarithmic amplitude response method
§ 12.4. Synthesis of automatic control systems based on frequency quality criteria

6. PECULIARITIES OF FREQUENCY DOMAIN SYNTHESIS OF CONTROL SYSTEMS

Construction of absolutely forbidden areas for Bode diagram is our original and effective method of control algorithms design [Besekerskiy, Nebylov, 1983; Nebylov, 2002; Nebylov, Watson, 2016]. We consider the input signal with unknown spectral density but known dispersions or maximum values of three or two derivatives. The additive input noise is a white noise with the spectral density S_v. The total error consists 2 components due the noise action $D_{e\,v} = D_e^0, e_{vp} = e_M^0$ and due the signal dynamics e_g.

Write the formula for the first component

$$D_{e\,v} \approx S_v \omega_0 l/2, e_{vp} \approx 3\sqrt{S_v \omega_0 l/2}\,.$$

Determine the maximal possible value of base frequency ω_{0v}, at which excess the accuracy requirement will be broken even in the case of zero dynamic error: $\omega_{0v} = \frac{2D_e^0}{S_v l}$

or $\omega_{0v} = \frac{2\left(e_M^0\right)^2}{9 S_v l}$.

The inequality $\omega_0 \le \omega_{0v}$, which realization is the necessary condition for obtaining the required accuracy, is possible to draw as the absolutely forbidden area in the Bode diagram plane of open loop system. For construction of this absolutely forbidden area it is necessary to mark the points

$$\omega'_{0v} = \frac{2D_e^0}{S_v}\left(\text{or}\ \omega'_{0v} = \frac{2\left(e_M^0\right)^2}{9S_v}\right), \omega''_{0v} = \frac{\omega'_{0v}}{2}, \omega'''_{0v} = \frac{\omega'_{0v}}{3}$$

on abscissa axis and to draw the straight lines with inclinations – 20 dB/dec,– 40 dB/dec and –60 dB/dec accordingly through them. Such construction is shown in Figure 1, at the right part.

The absolutely forbidden area at the registration of dynamic error only is constructed also in the left part of the figure.

Its boundary is formed also by straight lines segments of single, double and triple inclination, which position is determined by the base frequencies

$$\omega'_{0g} = \sqrt{D_1/D_e^0}, \omega''_{0g} = \sqrt[4]{D_2/D_e^0}, \omega''_{0g} = \sqrt[6]{D_3/D_e^0}$$

in the case of given dispersions or

$$\omega'_{0g} = g_M^{(1)}/e_M^0, \omega''_{0g} = \sqrt{g_M^{(2)}/e_M^0}, \omega'''_{0g} = \sqrt[3]{g_M^{(3)}/e_M^0}$$

in the case of given maximal values.

It is visible from the figure, that the allowed area for Bode diagram appears restricted both from below and from above.

If the condition $\omega_{0v} > \omega_{0g}$ for frequencies ω_{0v} and ω_{0g} with any identical superscript is broken, then it testifies the impossibility to obtain the required accuracy at use of Bode diagram with the appropriate inclination. But realization of this condition is not enough for deriving the required accuracy. For example, if $\omega'_{0v} < \omega'_{0g}, \omega''_{0v} > \omega''_{0g}$, $\omega'''_{0v} > \omega'''_{0g}$, then the obtaining of required accuracy in system with Bode diagram of single inclination is impossible.

However, even at $\omega'_{0v} > \omega'_{0g}$ it is still impossible to claim, that the selection of Bode diagram of single inclination can ensure the required accuracy. For validity of such statement the inequality $\omega'_{0v} > \omega'_{0g}$ should be fulfilled with the particular reserve

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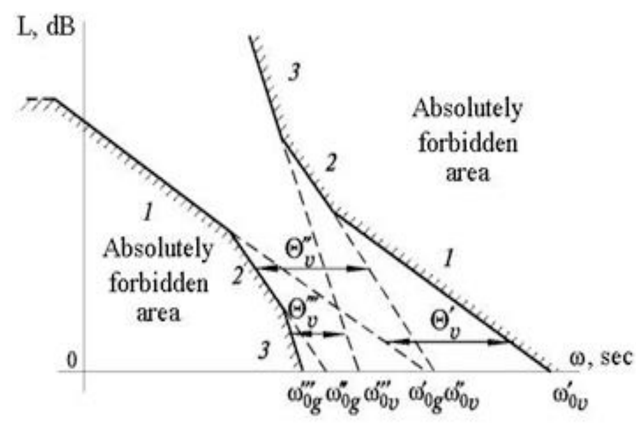

Fig.1. Forbidden areas at Bode diagram.

If the condition $\omega_{0v} > \omega_{0g}$ for frequencies ω_{0v} and ω_{0g} with any identical superscript is broken, then it testifies the impossibility to obtain the required accuracy at use of Bode diagram with the appropriate inclination. But realization of this condition is not enough for deriving the required accuracy. For example, if $\omega'_{0v} < \omega'_{0g}, \omega''_{0v} > \omega''_{0g}$, $\omega'''_{0v} > \omega'''_{0g}$, then the obtaining of required accuracy in system with Bode diagram of single inclination is impossible. However, even at $\omega'_{0v} > \omega'_{0g}$ it is still impossible to claim, that the selection of Bode diagram of single inclination can ensure the required accuracy. For validity of such statement the inequality $\omega'_{0v} > \omega'_{0g}$ should be fulfilled with the particular reserve.

Analytical analysis of possibility to obtain the required accuracy is possible. The opportunity of reaching the required accuracy with the account of dynamic error and error from interference can be estimated. For this purpose it is necessary to test the realization of above inequalities, meaning that

$$\Theta_v = \omega_{0v}/\omega_{0g} = 2\left(D_e^0\right)^{1+1/2l}\left(lD_l^{1/2l}S_v\right)^{-1}$$

at restriction of error dispersion and

$$\Theta_v = \omega_{0v}/\omega_{0g} = 2\left(e_M^0\right)^{2+1/l}\left[\left(9lg_M^{(l)}\right)^{1/l}S_v\right]^{-1}$$

at restriction of maximal error. Then the following requirements are developed:

$$D_e^0 \ge \left[\frac{(1+2l)^{2l+1}}{4^{2l}}D_l S_v^{2l}\right]^{\frac{1}{2l+1}},\ e_M^0 \ge \left[\frac{9^l(1+2l)^{2l+1}}{8^l l^l}g_M^{(l)}S_v^l\right]^{\frac{1}{2l+1}},$$

or at $l = 1$

$$D_e^0 \ge 1.19\left(D_1 S_v^2\right)^{1/3},\ e_M^0 \ge 3.12\left(g_M^{(1)}S_v\right)^{1/3}, \qquad (1)$$

at $l = 2$

$$D_e^0 \ge 1.65\left(D_2 S_v^4\right)^{1/5},\ e_M^0 \ge 3.97\left(g_M^{(2)}S_v^2\right)^{1/5}, \qquad (2)$$

at $l = 3$

$$D_e^0 \ge 2.13\left(D_3 S_v^6\right)^{1/7},\ e_M^0 \ge 4.60\left(g_M^{(3)}S_v^3\right)^{1/7}. \qquad (3)$$

If the inequalities (1) - (3) are not fulfilled, then the system synthesis problem with the given precision factor has no solution. If these inequalities are fulfilled with the great reserve, then the synthesis can be produced practically without taking into account the disturbance.

Case of action as the sum of addends with the numeric characteristics of derivatives can be considered also. The above-described graph-analytical method with some additions can be effective also at optimization of system in which the reference action is the sum of casual independent centred components

$$g(t) = \sum_{j=1}^{l} g_j(t),\ l > 1, \qquad (4)$$

for each of them the dispersions (or maximum values) of some, probably, different derivatives $M\left\{\left[g_j^{(i)}(t)\right]^2\right\} \le D_{ij}$ (or $\left|g_j^{(i)}(t)\right| \le g_{jM}^{(i)}$), $K_j \le i \le N_j$ are restricted. An additive interference on system input is still white noise with known level of spectral density S_v.

The system optimization by criterion $\overline{D}_e \to \min$ (or $e_M \to \min$) is made as follows.

At first the initial approximate "overestimated" value of control error measure D_e^0 (or e_M^0) should be determined. It can be made according to the numerical characteristics of action derivatives components only of that order, for which such characteristics are available for all components. If these derivatives have the order *k*, i.e. $\max_j K_j \le k \le \min N_j$, then at reviewing *k*-th order system with *k*-th order astatism and optimal parameters, the formulae (1)-(3) and similar to them allow to express an error measure analytically through the values $D_k = \sum_{j=1}^{l} D_{k_j}$ (or $g_M^{(k)} = \sum_{j=1}^{l} g_{jM}^{(k)}$) and S_v.

Then the absolutely forbidden areas for Bode diagram should be constructed, according to the requirement $\overline{D}_e \le D_e^0$ (or $e_M \le e_M^0$) at the separate registration of characteristics for each of action components and value S_v for the interference. In outcome, *l* partially overlapped forbidden areas in the left bottom and one — in the right top of Bode diagram plane are shaped.

After that l forbidden areas at the left bottom part of Bode diagram plane in one resultant area are being united. Its boundary ordinates determine the magnitudes preset by the graphs in logarithmic scale according to summing rules. The boundary of obtained resultant forbidden area is located not below the boundaries of joined forbidden areas and, unlike them, can have curvilinear segments. Thus, the possibility of observing only two forbidden areas is ensured. The width of allowed "corridor" between them characterizes the possibility of control accuracy raise in relation to a level appropriate to the value D_e^0 (or e_M^0).

The further procedure of optimal Bode diagram determination does not differ in essence from described above procedure with reference to a case of action representation, which is not separated on components.

Example. $l = 3$, $K_1 = 2$, $N_1 = 3$, $K_2 = 1$, $N_2 = 2$, $K_3 = N_3 = 2$

$D_{21} = 3.6 \cdot 10^{-6}\ \mathrm{m}^2/\mathrm{sec}^4$, $D_{31} = 1.7 \cdot 10^{-12}\ \mathrm{m}^2/\mathrm{sec}^6$, $D_{22} = 9.10 \cdot 10^{-4}\ \mathrm{m}^2/\mathrm{sec}^4$, $D_{12} = 1.3 \cdot 10^{-4}\ \mathrm{m}^2/\mathrm{sec}^2$, $D_{23} = 4.0 \cdot 10^{-8}\ \mathrm{m}^2/\mathrm{sec}^4$, $S_v = 0.055\ \mathrm{m}^2/\mathrm{Hz}$

It is required to optimize system by the criterion $\overline{D}_e \to \min$.

As for each of three action components the second derivative is restricted, then $k = 2$ and

$$D_2 = \sum_{j=1}^{3} D_{2j} = 9.14 \cdot 10^{-4}\ \mathrm{m}^2/\mathrm{sec}^4 .$$

The evaluation on the basis of (2) gives $D_e^0 = 1.70 D_2^{1/5} S_v^{4/5} = 0.0414\ \mathrm{m}^2$.

The constructed boundaries of four absolutely forbidden areas for Bode diagram are drown by dashed lines in Fig. 2, where

$$\omega'_{0v} = 2 D_e^0 / S_v, \omega''_{0v} = \omega'_{0v}/2, \omega'''_{0v} = \omega'_{0v}/3,$$
$$\omega'_{0g} = \left(D_{12}/D_e^0\right)^{1/2},$$

$$\omega''_{0g} = \left(D_{23}/D_e^0\right)^{1/4},\ \omega'''_{0g} = \left(D_{31}/D_e^0\right)^{1/6},\ \omega_{cg1} = \left(D_{31}/D_{21}\right)^{1/2}$$

The value D_{22} has no fracture of boundary on frequency $\omega_{cg2} = \left(D_{22}/D_{12}\right)^{1/2}$, because $\omega_{cg2} > \omega'_{0g}$. The boundary of resultant absolutely forbidden area integrating three forbidden areas in the left bottom of Figure 2 is drawn by the bald line.

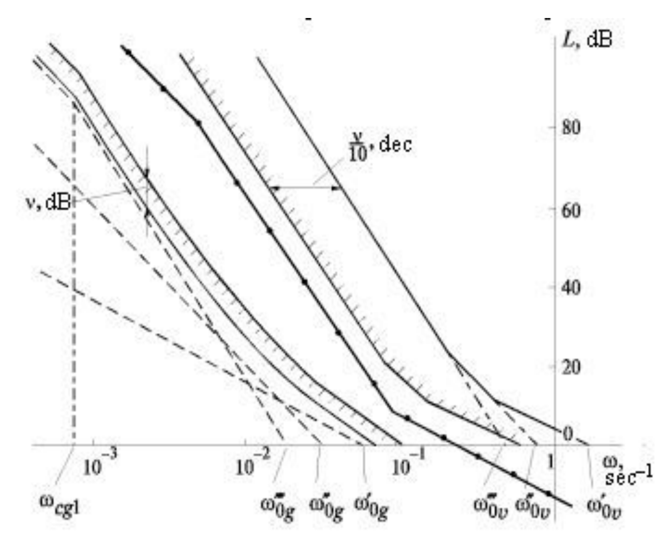

Fig. 2. Bode diagram construction.

As the width of obtained allowed "corridor" exceeds the quarter decade, it can be narrowed down. Select the contraction parameter $\nu = 4.5$. Boundaries of narrowed "corridor" are marked by leader in Figure 2. Left of them is raised on 4.5 dB, right one is shifted to the left on 0.45 dec. The checking precision factor value $D_e^1 = D_e^0 / 10^{0.45} = 0.0165\ \mathrm{m}^2$ corresponds to these new boundaries.

The Bode diagram selection variant, passing in the middle part of allowed "corridor", is marked by line with points.

7. CONCLUSIONS

The peculiarities of Russian educational system for training the aerospace students in the field of automatic control and navigation were discussed. This system involves 3 educational levels: bachelor, master and specific Russian level “specialist” that permits to prepare the high qualified engineers for aerospace industry and research centers.

The original frequency domain method of control system synthesis on the basis of forbidden areas for Bode diagram was explained. This method is especially effective in the synthesis of aerospace automatic control systems due to two circumstances.

Firstly, the input does not require knowledge of the full spectral-correlation model; only numerical characteristics are used, such as restrictions on the root-mean-square or maximum values of the derivatives. Only such numerical characteristics are reliable for the inertial sensor errors, as well as for the motion parameters of the aerospace controlled object itself [Nebylov, 2013; Nebylov, Watson, 2016].

Secondly, the method allows for the synthesis of a system to control for only the root-mean-square, but also the maximum control error, which, when solving many engineering problems, is the most important indicator of the quality of control. The development of the Kalman and post-Kalman filtering methods led to the practical abandonment of the use of maximum error and the predominant use of the root-mean-square error. The proposed method allows to make the formulation of the problem of control system synthesis more relevant to the requirements of engineering practice.

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REFERENCES

Besekerskiy V.A., Nebylov A.V. (1983) Robust systems of automatic control. Nauka, M. 241 p. (in Russian).

Mozhaysky Military Space Academy (2019). List of specialties, URL: http://academy-mozhayskogo.ru/joiners/demands

Nebylov, A.V. (2004) Ensuring control accuracy. Springer-Verlag, Heidelberg, Germany.

Nebylov A.V. (2013). Aerospace Sensors. Momentum Press, USA, 349p.

Nebylov A., Watson J. (2016). Aerospace Navigation Systems. Wiley & Sons, UK, 392 p.