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Automatic Control Theory as a Part of Aerospace Training in Russia

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Abstract: The article describes the history and achievements of Russian scientists in the field of automatic control theory and systems. The great role of automatic control methods in the essential space projects was shown. The example of automatic landing of aerospace plane Buran was considered. The long scientific activity of acad. Boris E. Chertok as the deputy General Designer for automatic control was analyzed. The particular methods of robust systems synthesis in frequency domain popular in Russia are analyzed and their effectiveness in aerospace projects was shown. The main Russian Universities training students in aerospace technologies are listed.

Keywords: automatic control theory, students training, aerospace technologies, frequency domain.

1. INTRODUCTION

On October 4, 1957, the Soviet Union launched the world's first artificial Earth satellite. This not only opened a new era in the history of mankind, but also made the USSR a superpower. On April 12, 1961, when the world's first manned space flight was made by test pilot Yuri Alekseevich Gagarin, the Soviet Union confirmed its authority. Both events became possible thanks to the development of the R-7 missile under the leadership of the great General designer of OKB-1 (now JSC RSC “Energya”) Sergei Pavlovich Korolev.

The last event was more expected in the world. Many things related to the state of scientific research and technical education in the USSR were demonstrated at the First World Congress of IFAC, which was held in the summer of 1960 in the building of Moscow state University named after M.V. Lomonosov. In the number of presentations at this Congress, the Soviet Union was first and even ahead of the United States.

Interest to the country, which launched both the first satellite and the first man into space, was huge and extended not only to scientific results, but also to the structure of scientific and engineering centers, as well as to the system of technical, physical and mathematical education.

Much has changed since that time. In the place of the former Soviet Union, the Russian Federation tried in every sense to imitate the Western way of development, abandoning its recent past at that time, even somewhere positive experience. In the education of the 1990s, a two-level "Bologna" system (bachelor-master) was adopted, and even now this decision causes a lot of controversy, and for some, especially important, aerospace engineering specialties, as a result, a single-stage curriculum for training specialists was retained. The Ministry of Defense of the Russian Federation, most often, does not recognize the bachelor's degree, and the universities subordinated to it do not consider it possible to prepare demanded specialists during 4 years.

The transition to a three-level education system with the introduction of the highest degree-doctor of philosophy-has not been implemented, while the degrees of candidate of sciences and a completely unique degree of doctor of Sciences are preserved. Changes in higher education and science will obviously continue, but more cautiously. Since 2018, these changes are carried out by the new Ministry of Science and Higher Education of the Russian Federation under the leadership of Mikhail Kotyukov, but science 2020 – under the leadership of new minister Valery Falkov. The Ministry is directly in charge the Russian Academy of Sciences also.

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

2. RUSSIAN AEROCPASE UNIVERSITIES

In the modern Russian Federation, the number of universities teaching aerospace specialties is 21. All of them are also major research centers that develop this area of science. Their list is presented below. All 21 universities are state-owned, located in 15 cities, including 4 universities in Moscow and the same number in St. Petersburg. We would especially like to note the St. Petersburg State University of Aerospace Instrumentation (SUAI), where the authors of this article works – the only University in the world with a name dedicated directly to aerospace instrumentation. The reason is quite simple - it is in St. Petersburg where 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 Astronautics. Note also located in St. Petersburg, the Military space Academy named after A.F. Mozhaisky, where specialists are trained for all Russian cosmodromes (Chertok B.E, 2016; Mozhaysky, 2020).

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

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1. Baltic State Technical University "Voenmech" named after D.F. Ustinov
2. Bauman Moscow State Technical University
3. Irkutsk State Technical University https://en.wikipedia.org/wiki/List_of_aerospace_engineering_schools - cite_note-115
4. Kazan Aviation Institute https://en.wikipedia.org/wiki/List_of_aerospace_engineering_schools - cite_note-113
5. Komsomolsk-on-Amur State Technical University https://en.wikipedia.org/wiki/List_of_aerospace_engineering_schools - cite_note-123
6. Moscow Aviation Institute https://roundranking.com/universities/moscow-aviation-institute.html?sort=O&year=2019&subject=SO
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 Universityhttps://en.wikipedia.org/wiki/List_of_aerospace_engineering_schools - cite_note-122
11. Omsk State Technical Universityhttps://en.wikipedia.org/wiki/List_of_aerospace_engineering_schools - cite_note-121
12. Perm National Research Polytechnic University]
13. Rybinsk State Aviation Technical University https://en.wikipedia.org/wiki/List_of_aerospace_engineering_schools - cite_note-117
14. **Saint Petersburg State University of Aerospace Instrumentation** https://en.wikipedia.org/wiki/List_of_aerospace_engineering_schools - cite_note-118
15. Saint Petersburg State University of Civil Aviation
16. Samara State Aerospace University
17. https://en.wikipedia.org/wiki/List_of_aerospace_engineering_schools - cite_note-111 Siberian State Aerospace University https://en.wikipedia.org/wiki/List_of_aerospace_engineering_schools - cite_note-112
18. Skolkovo Institute of Science and Technology (Skoltech)
19. South Ural State University https://en.wikipedia.org/wiki/List_of_aerospace_engineering_schools - cite_note-116
20. Ufa State Aviation Technical University
21. Voronezh Aviation Engineering University https://en.wikipedia.org/wiki/List_of_aerospace_engineering_schools - cite_note-119

More than a half of these universities are universities of a wide profile, in which only a small proportion of students specialized 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 the 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 given 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.

A wider range of space specialties is presented in the list below.

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 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 RAN, 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 Ground 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 quality electronics systems;
11. JSC Concern «Almaz-Antey» is one of the largest holdings of the military-industrial complex of Russia which part 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:

1) JSC “Russian Research Institute of Radio Equipment” (RRIRE);
2) JSC «Russian Institute of radio navigation and time».

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

Unlike training for other engineering specialties (Maurício C. de Oliveira, 2017; O'Brien, 2012; Shaila, 2016), 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 Regulation 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 system stability and performance by the step response.
§ 8.5. Approximate assessment of the type of the transition process on the real frequency response.
§ 8.6. Root method.
§ 8.7. Vyshnegradsky diagram.
§ 8.8. Integral estimates.
§ 8.9. Frequency quality criteria.
§ 8.10. Regulatory Sensitivity.

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 (Nebylov, 2004; Nebylov, Watson, 2016). We consider the input signal with unknown spectral density but known dispersions or maximum values of three or two dispersions of derivatives. The additive input noise is a white noise with the spectral density S_v. The total error consists of 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 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 1.

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 of derivatives.

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 margin.

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.

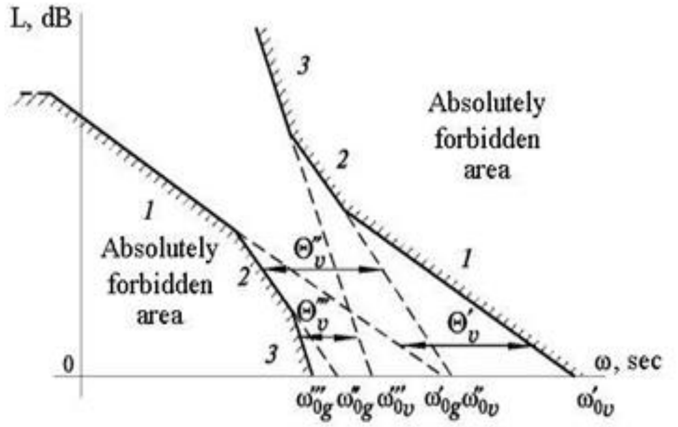

Fig.1. Forbidden areas at Bode diagram.

7. AUTOMATIC LANDING OF RUSSIAN AEROSPACE PLANE “BURAN” AT THE AERODROME

In the history of Soviet and then Russian cosmonautics, an important breakthrough was the launch of a reusable aerospace craft "Buran", which was an analogue of the American "Space Shuttle". "Buran" was created under the leadership of the outstanding chief designer G. E. Lozino-Lozinsky, who previously worked out the basic design ideas on the aerospace hypersonic aircraft "Spiral", weighing 52 tons. Made by the order of the Ministry of Defense of the USSR, the Soviet "Shuttle" differed greatly in weight and had some design features characteristic only for it. Also for its launch into orbit the largest at that time space transport system "Energya" was created. An important requirement of the customer was the presence of an automatic control system of the spaceship in case of inability of the crew on board to control this vehicle. Of particular difficulty was to make an automatic landing system "Buran", as it had to land in the same way as a conventional aircraft. Soviet scientists, engineers and programmers managed to create it by conducting a series of full-scale experiments on the aircraft analog with crews led by I.P.Volk (main) and A.S. Levchenko (backup).

The onboard control system consisted of various software systems, most of which were based on the IBM System/370 computer. Also, in addition to using standard IBM commands, many original General-purpose commands were added that have no analogues in the standard set. Two sets of software on four hardware-parallel "BISER-4"computer and hardware comparator, allows automatic disconnection consecutive two computers in case of emergency results (4 basic + 4 reserve), were perched onboard the vehicle. Software development for spacecraft ground systems used structural program design technology using the DIPOLE language, and the LAX language was used to solve the modeling problems. The software and operating system were written in PROL2 (analogous to PROLOGUE) and Assembler/370. In SOFTWARE development, the concept of R-technology (R-machine and R-language) was widely used using the ASFO programming and debugging of automatic system. The use of computer technologies developed in the USSR, allowed in a short time to develop software systems with a volume of about 100 Mb. In case of failures of the rocket blocks of the first and second stages of the launch vehicle, the control system of the Orbiter ensures its emergency return to earth in automatic mode.

On the basis of the real-time language PROL2 and a problem-oriented language for the development of programs for ground tests DIPOLE and created by the Scientific and Production Center of Automation and Instrumentation named after academician N. A. Pilyugin language LAX in 1996 the programming language DRAGON was created, used to this day for various tasks. Programs, especially virtual machines, were mostly written in Russian by the block algorithm method (which later formed the basis for the creation of the state standard GOST 19.70-90, which students use today), Assembler/370 was used to save memory of the Central system.

The landing process took place in two major stages:

1. "Buran" descended accordingly the estimated trajectory to an altitude of 6300 m. (Nebylov A., 2013; Nebylov A., Watson J., 2016).

2. Used radio navigation system, and air traffic control system "Vympel", landing with providing a stable supply of data on the weather, the exact coordinates of the runway of the spaceport "Baikonur", glide path, etc.

In the beginning of the descent the aerodynamic controls were used only for balancing the orbital aerospace plane (ASP), and when reaching the speed pressure q=10 kg/m^2 they were connected also to the control of angular motion, and increasing the effectiveness of aerodynamic controls, and velocity head, they gradually take on the functions of governing engines. To minimize fuel consumption, the engines of United Propulsion System were switched off at q=50 kg / m^2 in the roll channel and at q=100 kg / m^2 in the longitudinal channel.

The task of the pre-landing maneuvering is to bring the ASP to the beginning of the approach trajectory to the key point (KP), located at an altitude of 4 km in the vertical plane passing through the runway axis, with the orientation in it (in the plane) of the velocity vector. The ASP motion parameters in KP were severely limited by coordinates, speed, angle of trajectory and the deviation from the landing course. Their implementation is achieved by the scheme of motion, which provides a correspondence between the available energy of the ASP and the energy required to bring it into the KP. The energy is regulated by changing the length of the trajectory and the program speed head (aerodynamic quality control), and in the subsonic region - also by changing the angle of disclosure of the air brake. Control of the movement of ASP is carried out by forming at the beginning of the pre-landing maneuvering section in accordance with the current state of ASP a spatial reference trajectory (and its subsequent tracking), which can be rebuilt during the flight if the energy state of ASP does not meet the specified requirements.

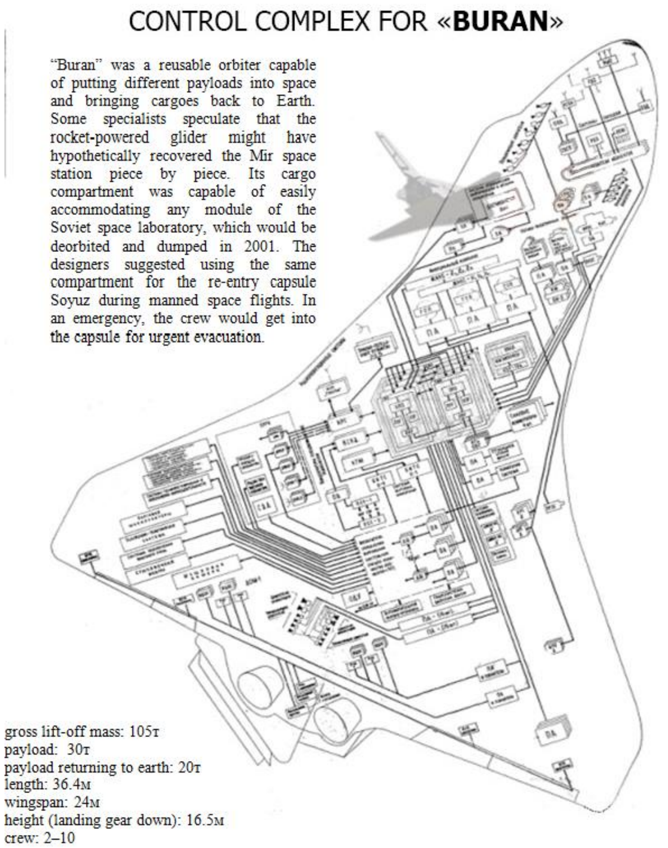

Fig. 2. Block – diagram of the ACS of "Buran"

In the vertical plane at speeds corresponding to M not less than 0.8, the reference trajectory is formed by constructing a program dependence of the altitude corresponding to the nominal speed head on the remaining range along the" trace " of the trajectory. At modes with M<0.8 the flight altitude control is implemented relative to the specified state at the end of the pre-landing maneuver (terminal control).

When we have deficiency of energy to increase the length of the ASP flight as a reference is used the dependence of the minimum velocity head from the altitude $q_{\min}(H)$, providing the maximum quality and when it is abundant - the dependence of the maximum dynamic pressure from flight altitude $q_{\max}(H)$, providing the greatest dissipation of energy.

The final phase of the descent section in the atmosphere is the approach to the landing and the actual landing of the aircraft on the runway with the specified motion parameters. Approach and landing are determined by the following two features:

* the first - the lack of engines that provide landing on the traditional aircraft scheme, and

* the second - relatively small aerodynamic Lift-to-Drag ratio ($K_{\max}$=5.6) in this section of the flight.

Ground studies and tests were carried out via mathematics and semi-actual modeling on the Full Scale Stand of Equipment (FSSE), flight tests were carried out on the TU-154 flying laboratory and BURAN Analogue, built by NPO MOLNIYA.

Despite fears and doubts about the feasibility, the automatic landing of the Soviet "Shuttle" was successful. This event marked the beginning of new directions in the development of science and marked the beginning of bringing educational programs and courses to the modern state. At November 25th, 2019 the 25th anniversary of "Buran's" flight was celebrated.

8. 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 has been developed in (Nebylov, 2004) and is still widely used at different Russian design centre's for rough estimation of acceptable control laws and control quality parameters. It was used at some control loops design for the Russian ASP "Buran", especially for its landing control and precise navigation systems.

The construction of «Buran» and the successful flight in automatic mode, including automatic horizontal landing at the airfield, was one of the highest achievements of Russian cosmonautics. The features of this test flight were briefly described in the article. This information may be useful for developers of other aerospace control systems.

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