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## Chapter 8

# THE DEVELOPMENT OF SYSTEMS OF AUTOMATIC FLIGHT CONTROL OF ROCKETS IN THE USSR, 1935-1939*

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Systems of automatic flight control for rockets and space vehicles differ from each other in many respects, and the history of their creation took two almost independent lines of development. In the USSR, both of these developmental lines are connected with S.P. Korolev, since the first automatic systems of stabilization were tested in flight on the cruise missiles "216" and "212," created under his management, and the first orientation system for a space vehicle was installed on the automatic interplanetary space station, Luna-3. This report examines only the initial stage in the creation of automatic systems for stabilizing cruise missiles in flight.‡

The first experimental rockets launched in the 1930's showed unstable flight characteristics in the absence of automatic systems for control. Theoretical studies, for example the work of M.K. Tikhonravov,[1] discussed the possibility of obtaining stability without automatic systems, using the motion of the rocket around the center of mass during its passage through the air, but left open a question about the stability of the center of the rocket's mass. Experience obtained during the first flight tests and theoretical calculations nevertheless disclosed the fundamental instability of vertically ascending rockets and required the creation of corresponding automatic systems of stabilization.

A system of automatic control for rockets in vertical ascent (for example meteorological rockets) was developed at the Jet Propulsion Research Institute (RNII), and consisted of a gyropneumatic stabilizer with one free gyroscope, RA-2 (rocket automatic machine during two stabilizations). It was completed and manufactured in the first half of 1937. The schematic diagram of this automatic system of stabilization appears in Fig. 1. [Figures were not furnished by the USSR Academy of Sciences.]

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‡ Ed. Note: The term "cruise missile," as used in this study, refers to rocket-powered aircraft. For details of these machines, see Ye. S. Shchetinkov, "Development of Winged Rockets in the USSR, 1930-1939." First Steps Toward Space, IAA History Symposia Vol. 1, (AAS History Series Vol. 6), 1985, pp 247 ff.

Its fundamental characteristics were: accuracy in stabilization of flight to $1^o$, duration of continuous operation (with a reserve of compressed gas) of 1 min, predicted maximum altitude of the rocket ascent, 12-15 km. The application of one free gyroscope made retention in the assigned limits possible in only two angles. The angles selected, which provided the verticality of the axis of symmetry of the rocket, while rotating the missile body around this axis, meant the rocket remained unguided. Consequently, this system was incomplete, but it satisfied the stated requirements since the rotation of the rocket around its axis of symmetry did not disturb the assigned character of a vertical flight trajectory. This automatic system of stabilization was not tested in flight, because in 1937 primary attention was directed toward the creation of rocket cruise missiles. This occurred because the available rocket motors provided insufficient thrust needed for a vertical climb carrying large payloads, while their application to cruise missiles made it possible, several times, to increase the weight of the payload.

The first cruise missile, which contained an automatic system of stabilization, was rocket "216," manufactured and tested in the period 1933-1936 and described in reference 2. It contained a gyropneumatic automatic system GPS-2, with one free gyroscope. This made control possible only in the selected pitch angle and roll attitude. This selection was hardly optimum, because an unguided cruise missile or glider is incapable of completing its flight without losing its assigned direction. Therefore it would probably have been more rational to select another combination that maintained the angles of pitch and yaw. Only an automatic system of stabilization that supported within assigned limits all three angles can determine aircraft attitude and ensure the stability of flight. Tuning the GPS-2 automatic system of stabilization, and using the routine calculation of static stability and effectiveness of controls, provided corresponding coefficients. Structurally, GPS-2 was close to the automatic system of stabilization GPS-3 described below.

The gyropneumatic stabilizer GPS-3, which began development in 1935, underwent ground tests during 1936-1937. It was intended for installation on the more powerful rocket cruise missile "212," described earlier by Shchetinkov.[2] GPS-3 was capable of holding three angles in the assigned limits (pitch, yaw, and roll). This caused use in its schematic of two free gyroscopes. Since reference 2 gives photographs of GPS-3, we will restrict our photograph to one of the installations for the ground-based final adjustment of this automatic system of stabilization (Fig. 2). As can be seen from this photograph, the ground test bench equipment made it possible to deflect the thrust of the rocket "212" with the GPS-3 installed. The scales for the measure of the pitch and yaw angles are well visible in the photograph. The piston stroke of the control actuators were transmitted to rudders whose rotation could be measured. This installation made it possible to obtain the experimental angles of deflection of the controls and the angles of deflection of the missile body (in this case with GPS-3), that produced static adjusting of the control loops.

Theoretically, participation of a pilot in control adjustments was completely eliminated during flight. But a problem arose during the bench tests of GPS-3, before flight tests began. In this case, it was necessary to decide two basic problems:

to determine the optimum value of static adjustment of GPS-3 and to consider theoretically the dynamic properties of the control system. Since the calculation of longitudinal stability and the selection of the corresponding adjustment of GPS-3 proved to be more complicated than analogous calculations of lateral stability, we will deal only with the longitudinal stability of the cruise missile.

A stability theory of motion of a cruise missile equipped with a gyroscopic automatic system for stabilization did not exist in 1937. Therefore, S.P. Korolev organized such an effort in his division of RNII. The results of this research on the longitudinal stability of the cruise missile "212" were published later as separate work.[3] The analysis showed the properties of axial motion of the cruise missile, which made it possible to select the desired characteristics of the automatic system of stabilization. Investigators found that the cruise missile's own aerodynamic damping of oscillations around the center of mass has a value sufficient for obtaining stable motion, and this made it possible to dispense with logic of control signals proportional to angular velocity. As is known, in the absence of an autopilot, aircraft longitudinal vibrations are composed of two oscillations--short-period, rapidly attenuating oscillations around the center of mass, and comparatively slow and considerably less intense oscillations of the motion of the very center of mass. The properties of a cruise missile are analogous.

The installation of an automatic system of stabilization of the GPS-3 type, whose static characteristic was reduced to direct proportionality between the pitch angle and the deflection of the elevator, led to an abrupt change in the character of the disturbed motion. In this case, the motion of the center of mass becomes a periodic and more stable than without GPS-3, while the oscillations around the center of mass become less stable, especially so in the presence of time delays in actuating the automatic system of control.

The task of determining the dynamic characteristics of GPS-3 thus arose. To obtain these characteristics under actual conditions, the completely assembled cruise missile "212" with the installed automatic GPS-3 was tested in the wind tunnel of the Central Institute of Aerohydrodynamics (TsAGI). In this test the machine was suspended in such a way that it would have the capability to complete oscillations in the longitudinal plane around the center of mass. During the test it was held in the necessary position by a functioning automatic GPS-3. The oscillations of the cruise missile itself and the deflection of the controls were recorded with chart recorders and on film. Different disturbances were introduced by deviating the axis of the cruise missile from the calculated position. The processed experimental data led to the conclusion that, for the stability analyses, it suffices to introduce a certain actuating time delay, whose value (found from the described experiment) subsequently was introduced into all calculations.

It turned out that in the presence of a constant effective delay, the stability of oscillations around the center of mass decreases with an increase in the velocity of flight, and this made the dynamic properties of the automatic system of stabilization agree with the maximum speed of flight necessary. The dependence of stability on flight speed proved to be essential for obtaining optimal control over an entire flight trajectory (which included periods with different flight speeds). It was thus proposed to refine the automatic control system to sense and change the difference between pitch angle and elevator angle dependent on current flight speed. This refinement was not realized because of the design complexity that would be introduced in GPS-3.

The flight trajectory of the cruise missile consisted of climbing while the motor was running, and of gliding. Theoretical studies showed that the stability of flight depended but little on the flight path angle. Therefore, although GPS-3 contained a certain "program of pitch" to obtain the desired flight trajectory, the program was unaffected by the regulating data of GPS-3.

The question of gust effect on the stability of flight drew special attention. Engineers developed a procedure of searching for optimum adjustment of the automatic system of stabilization, taking into account the characteristic external disturbances. This proved to be possible with the introduction of the integral criteria of the quality of transient processes. The results were published in connection with usual aircraft.[4]

The fundamental technical characteristics of the automatic system of stabilization, GPS-3, were: accuracy of retention of tilt angle on the order of 1°, total weight -16 kg, speed of rotation of gyroscopes 15000-17000 r/min. The GPS-3 was located in the cruise missile bay, ø300mm, with a length of 400mm. It was divided horizontally into upper and lower parts. The gyroscopic assemblies (the gyroscope in the gimbal suspension, arrestments, wind boxes), the control actuators, and the like were fastened to the board from two sides in such a way that the complete set of equipment for each gyroscope was located on either side. This layout of the automatic control system provided a series of advantages: its arrangement in the separate sections made it possible to carry out autonomous adjustment and tuning on the test benches separately from the cruise missile, without dismantling the GPS-3 as an entire section, and the arrangement of all equipment of each channel of stabilization on one side or the other on the board simplified work on the test benches during tuning of the corresponding channel.

After the flight tests it was possible to judge the work of the automatic system of stabilization in flight. Chart recorders registered the deflections of controls as a function of time; moreover, the cylinders on which the recording were made were placed in special armored containers, which guaranteed survival of the recording after the cruise missile struck the Earth.

While GPS-3, intended for cruise missile "212," was under development, work began on an analogous automatic system, GAT-3. The GAT-3 was produced for the cruise missile "201," which was designed for launch from beneath the wing of an aircraft. GAT-3 was also placed in a separate missile bay, but as can be seen from the photograph (Fig. 3), its design formulation was different: both gyroscopic units were placed on one side of the board, and control actuators located in the tail section (in the photograph, the cylinders of three control actuators are clearly visible. All of the automatic control systems (RA-2, GPS-2, GPS-3, GAT-3) were constructed under the immediate direction of A.S. Pivovarov.

Flight tests of cruise missiles equipped with automatic systems of stabilization amounted to four cruise missile launchings of "216" (1936), and two launchings of "212" (1939). The launchings in the "216" series gave only one relatively successful flight, with a loss of stability after liftoff at 500m. As far as the launchings of "212" were concerned, in the first flight the control process took a normal course, and even visual observation of the initial phase of the flight convinced engineers that the automatic system of stabilization countered the perturbations of wind gusts in flight. Unfortunately, the flight was interrupted by the unexpected opening of the parachute intended for the descent of rocket to the earth at the end of is gliding period. The second flight was unsuccessful, apparently because the automatic system of stabilization failed to function. Unfortunately, the starting catapult subjected the missile to excessive acceleration and vibration loads. The automatic system of stabilization apparently did not withstand the corresponding dynamic loads.

If we examine these automatic systems of stabilization from the contemporary point of view, one can see special features that are presently still used on carrier rockets. This makes it possible to consider the Soviet rocket automatic systems of control designed during 1936-1939 as the precursors of those used in the USSR today. Although the automatic systems of stabilization described above were intended for cruise missiles, they already possessed the following important special features: independence of control based on the application of the two gyroscopes; the existence of a timed program (program of pitch), and inflight recording of their work in flight (using an analog of contemporary telemetry). At the same time, a series of other special features distinguished them from contemporary systems--the use of pneumatic gyroscopes and control actuators instead of electrical ones, the absence in the logic of control of signals proportional to angular velocities, and the use of air vanes. The last two features of these automatic systems of stabilization were developed to meet the requirement of flight through the air.

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