УДК 623.4.08

KNJAZSKY O.V., *engineer*
MOSIYCHUK S.Y., *engineer*
SHEVTSOVA T.M.
(Central Research Institute of Arms and Military Equipment of the Armed Forces of Ukraine)

Analysis approaches to construction management systems managed artillery (reactive) projectile of small caliber

Проведено аналіз можливих підходів до побудови систем управління керованих снарядів калібру 120 (122) -мм. Розглянуті автономні, неавтономні й комбіновані системи управління.

Ключові слова: система управління, керований снаряд, середньоквадратичне відхилення.

Проведен анализ возможных подходов к построению систем управления управляемых снарядов калибра 120(122)-мм. Рассмотрены автономные, неавтономные и комбинированные системы управления.

Ключевые слова: система управления, управляемый снаряд, среднеквадратическое отклонение.

Existing systems of control of the aircraft (LA) allow purposefully and in a wide range to influence the flight path of the projectile (including reactive), thus eliminating sight errors, the effects of the atmosphere impact, the initial conditions of launch and other factors that reject the projectile from the target.

As a result, the accuracy of shooting projectiles management system is significantly increased (guided artillery shells (GAS) «Krasnopol-M2», «Kvitnyk-E», rockets «Tornado-S») and increased shooting range by **under planning** for passive area of the trajectory (PAT) (Figure 1), and as a result, the effectiveness of solving combat missions increases significantly.

A classic uncontrolled artillery shell and a projectile reactive system of a salvo fire are the rotating projectile statically stable on a ballistic flight trajectory. As objects of control such shells are non-stationary. That is, on the active part of the trajectory (APT), its non-stationary nature is due to a wide range of flight speeds, and on the PAT - a change in both speed and flight altitude. The control of such shells is usually low due to high (up to 6 ... 13%) static stability, therefore, significant control points are needed for effective management. The optimal choice of control system (CS) for small-caliber shells can be successfully implemented taking into account both the features of the shells themselves and the military tasks that solve this kind of armament. The basic requirement for guided reactive shell (GRS) to (RSZV) and GAS caliber 120 (122) mm can be providing a medium-quadratic deviation (MQD) at 15 ... 100 m (depending on the type of military equipment). Necessary indicators of MQD of these shells can be achieved using non-autonomous, autonomous or combined control systems.

The construction of high-precision control systems (CS), the MQD of which is 15 ... 30 m, is perspective for non-autonomous control systems. These systems include, above all, a system of command telecontrol or a radio correction system. The main feature of these systems is that the command management is formed at the point of the shot (start). This greatly simplifies the CS onboard equipment.

The formation of the control algorithm in the specified system is carried out by the calculator according to data of the radar accompaniment of the projectile (rockets). The transfer of commands to the aircraft is carried out using the so-called command radio control line associated with the calculator of the predicted flight path of the projectile (rocket).

The ability of modern radars to accompany up to 40 projectiles in real time, as well as the ability of modern processor systems to solve the problem of prognosticating flight paths, creates the real preconditions for the creation of high precision shells with the radio correction system.

One of the significant advantages of the system of command radio control used in non-autonomous control systems is the ability to provide it with a variety of flight paths of the projectile (rocket) in the process of convergence with the target with relatively simple equipment. However, it should be noted that these systems, like all radio engineering systems, are subject to radio interference. According to expert estimates, at distances of 20 km, the failure of the

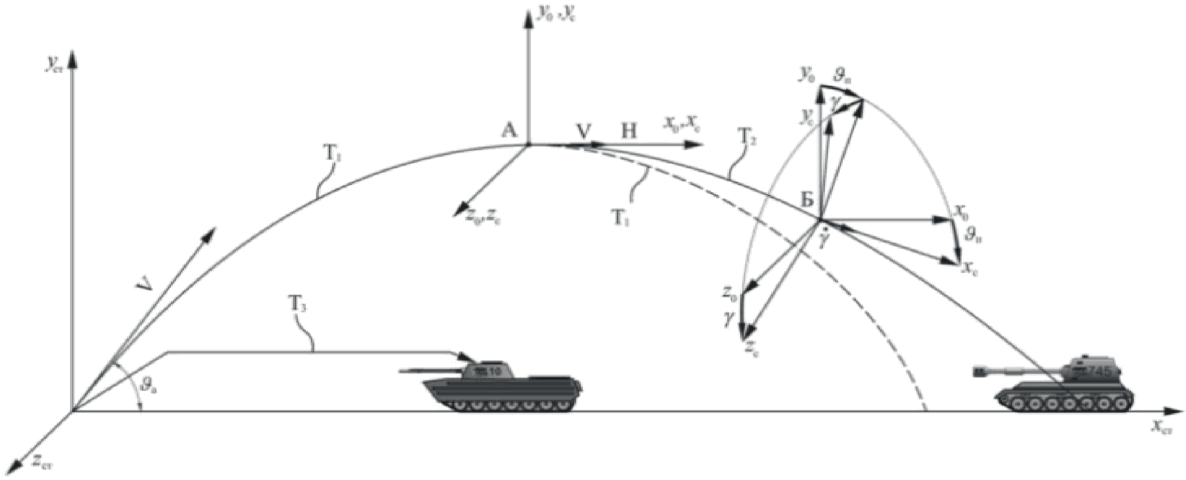

Fig. 1. Trajectory of the movement of the center
of the masses of the GAS

shells (projectile) with the radio correction system can be up to 40 m.

Autonomous systems after a cannon shot (the start of a reactive projectile from the start-up launcher does not require information links with the place of the shot (starting point), nor with the target (sighting point). Such systems are built as systems of automatic stabilization of flight parameters or programmatic change of flight parameters in accordance with the purpose of guidance (monoblock or cassette equipment). The equipment of autonomous stabilization systems is completely located on board the projectile. The system's readiness is determined by the time of preparation of gyroscopic devices and access to the power source mode. The time of preparation can range from a fraction of a second to tens of seconds (0,1 ... 60 s). The overall dimensions of the control system block, constructed on a modular basis, are determined mainly by the time of operation of the system, that is, the dimensions of the power supply sources, and the powdered pressure accumulators (PPAs) required for the operation of the executive bodies of the system. The precision of projectile with such systems may be from MQD 100 m, as the system accumulates its instrumental errors in proportion to the working time. The system can be used to improve the accuracy of the shells at small hours of operation (up to several seconds) and in the area of greatest angular deviation of the projectile, which is the first third of the APT. Independent control systems with a gyrostabilized platform or free-form inertial systems have high accuracy, but their use for projectile of 120 (122) mm calibers is problematic because their gear unit (without actuating elements) exceeds the dimensional sizes that allocated to the control system block. In addition, the time of preparation of these systems at the point of the shot (start) is tens of seconds, which can be compared with the time of a full volley 120 (122) mm of the reactive system. Inertial systems, the principle of which is based on the double vector integration of the acceleration of the object, have a high cost and their use without significant reduction of this value (for example, the use of MEMS technologies) is also problematic [1, 2].

Let's return to Figure 1. Note that the design of "onboard gyro devices" essentially depends on the trajectory of the movement of the center of mass GAS from the "point" of the beginning of the movement to the target. The "point" of the start of the projectile (rocket) movement is at the beginning of the coordinate system $Z_{CT} Y_{CT} X_{CT}$. The GAS comes from a cannon with an initial speed V at an angle Θ_0 tangent to the trajectory of the movement. The gyroscope on a projectile board simulates the reference coordinate system $Z_0 Y_0 X_0$ in relation to which the GAS coordinate system $Z_C Y_C X_C$ is determined by the angles of the bearings $\vartheta_П$ and the roll γ of the projectile when moving the GAS on a ballistic trajectory T_1 or T_2. Trajectory movement T_2 is occurs when, if after point A, there is a "under planning" of the projectile to increase the range of its flight. The dynamics of the gyroscope is given in the assumption that at the point A, the vectors of the kinetic moment of the gyroscope and the linear velocity of the center of the projectile mass coincide. When moving the center of masses of the GAS on the deck trajectory T_3, the position of the associated coordinate system relative to the reference is determined by the angle of the heel γ.

Potentially, based on the three-stage gyroscope, different variants of gyro devices can be constructed: 1 – gyrocoordinators (GRC) to measure the angle of inclination of rotating rolls of projectile; in this case, the axis of the suspension of the outer frame coincides with the longitudinal axis of the GAS; 2 – gyroscopic angle sensors measuring angles of inclination, course and pitch and the so-called gyroscopes of the direction measuring the angle of the bearing (a similar task is solved by angular displacement meters of the longitudinal axis of the projectile).

On the basis of low-cost technologies of micromechanical gyroscopes and accelerometers (MMG and MMA) can be constructed [3, 4]: gyrocoordinators; sensors of angular velocity of oscillations of the longitudinal axis GAS.

The development of gyro devices with pulsed overclocking of the hyromotics, which in the terminology are the pulsed gyroscopes, posed a problem in the formation of scientific foundations for their synthesis. At the same time, the known schools solved the problematic questions concerning the creation of the theory and methods for calculating pulsed gyrometers, the theory and methods for calculating the accuracy of three-stage gyroscopes with variable kinetic moment mounted on rotating rolls of projectiles moving with longitudinal and transverse constant and vibrational loads [5 – 7]. An expedient direction of improvement of on-board equipment for controlling dynamic projectiles, especially small ones, is the use of inertial measuring modules (IMMs) of low precision class (Low Cost). To such an accuracy class are IWMs on micromechanical gyroscopes and accelerometers. The autonomous application of low-accuracy precision IMMs is possible only in a limited time interval (tens of seconds) or in the submission mode with other navigation information sources. To date, there are some scientific publications [3, 5, 8], as well as reports on the practical development of MMA and MMA for rotary aircraft of type GAS, is the circuit engineering and metrology of the results of the measurement of the IMM, as well as software for the development of commands for steering control units.

Consider an example of an algorithm for processing information derived from two MMG, measuring axes which are located at an angle to the axis of rotation on the executive bodies of aircraft (GRC based on MMG).

Some types of MMG, having good sensitivity and moderate drift of the zero signal, have limits in the range of angular velocities (no more than 1000 deg/s). In this case, the measuring part of the GRC can be constructed on the basis of MMG, whose measuring axes are located at an angle of 90 in relation to the longitudinal axis of the aircraft (Fig. 2).

Output signals MMG have the form

$$\begin{cases} \omega_A = \omega_{yc} cos\,\varepsilon + \omega_{xc}\sin\varepsilon; \\ \omega_Б = -\omega_{yc}\cos\varepsilon + \omega_{xc}\sin\varepsilon. \end{cases} \qquad (1)$$

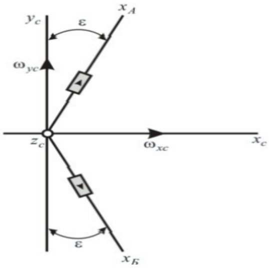

Fig. 2. The scheme of installation MMG

Projections of absolute angular velocities of the associated coordinate system $Ox_c y_c z_c$, whose position relative to the reference coordinate system is determined by the angles of the course Ψ, pitch Θ and roll γ, on its axis is determined by the following equations:

$$\begin{cases} \omega_{xc} = \dot{\gamma} + \dot{\psi}\boldsymbol{sin}\theta; \\ \omega_{yc} = \dot{\psi}\boldsymbol{cos}\theta\boldsymbol{cos}\gamma + \dot{\theta}\boldsymbol{sin}\gamma; \\ \omega_{zc} = \dot{\theta}\boldsymbol{cos}\gamma - \dot{\psi}\boldsymbol{cos}\theta\boldsymbol{sin}\gamma. \end{cases} \qquad (2)$$

For the case of a small angle Θ and the ratio of angular velocities $\dot{\gamma}$ $\dot{\psi}$, we find the sum of the signals (1) taking into account (2):

$$\omega_A + \omega_Б = 2\omega_{xc}\sin\varepsilon \approx 2\dot{\gamma}\sin\varepsilon.$$

Thus, having on board aircraft two MMG with the axes of sensitivity, deployed along the longitudinal axis at a certain angle, one can determine the angular velocity of the roll by correlation

$$\dot{\gamma} = \frac{\omega_A + \omega_Б}{2\sin\varepsilon}. \qquad (3)$$

To control rotating rolls, it is necessary to determine the functions of the sinus and cosine of the angle of the roll γ to convert the control signals from the reference coordinate system into the projectile. For this purpose, it is possible to pass the preliminary calculation of the angle of the roll γ by integrating the ratio (3), and directly obtain the functions sin γ and cos γ.

You can use other orientation options, such as cosine paths or the Rodriguez-Hamilton parameters. In the case of the use of the latter, the rotation of the related coordinate system $Ox_c y_c z_c$ regarding in a semi-angular $Ox_c^{/} y_c^{/} z_c^{/}$ on the angle γ can be matched to four Rodriguez-Hamilton parameters, of which only two are nonzero:

$$p_0 = \cos\frac{\gamma}{2},\ p_1 = \sin\frac{\gamma}{2}. \qquad (4)$$

By differentiating (4), $2\dot{p}_0 = -\dot{\gamma}p_1$; $2\dot{p}_1 = \gamma p_0$, we find trigonometric functions $\cos\gamma = 2p_0^2 - 1$; $\sin\gamma = 2p_0 p_1$.

The block diagram of the GRC on micromechanical gyroscopes is shown in Fig. 3

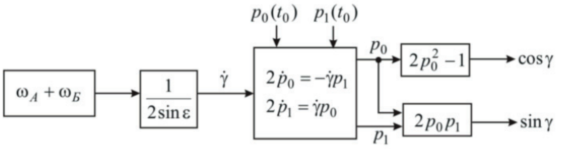

Fig. 3. Structural scheme of development cos γ and sin γ using the parameters of the Rodrigo-Hamilton.

On the basis of MMG and MMA can also be constructed sensors angular velocity and the angle of the GAS. The block diagram of the angular velocity sensor of the GAS roll using two counter-directional accelerometers, whose axis of sensitivity is perpendicular to the longitudinal axis of the object, is shown in Fig. 4

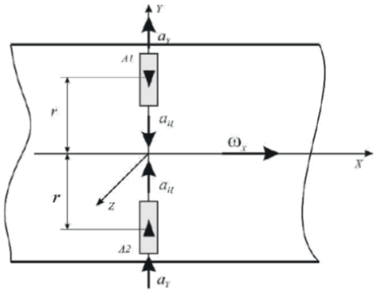

Fig. 4. Scheme for measuring the angular velocity of a small-caliber GAS roll with two MMAs

In the systems of the first a_{A1} and second a_{A2} accelerometers there will be an element a_Y due to linear acceleration of the center of mass of the system along the axis associated with the object, as well as centrifugal acceleration a_L, due to the presence of angular velocity ω_γ of the roll:

$$\begin{cases} a_{A1} = -a_Y + a_Ц, \\ a_{A1} = a_Y + a_Ц. \end{cases}$$

Given the dependence connecting the angular velocity of the roll and the acceleration of the centrifugal [9]:

$$a_Ц = \omega_\gamma^2 r,$$

We get a relationship to determine the angular velocity of the roll

$$\omega_\gamma = \sqrt{\frac{a_{A1} + a_{A2}}{2r}}.$$

This method for measuring the angular velocity of a GAS roll distinguishes a number of advantages: the measuring scheme allows you to directly measure the angular velocity of the projectile's roll ω_γ, and not the angular velocity of the object ω_X relative to the longitudinal axis X associated with the object, which in the general case differ in magnitude $\dot{\psi} \cdot \sin\theta$ (ψ – angular speed of search). This contributes to increasing the accuracy of the determination of the angle of the CAS roll; at large values of angular velocities, this measurement scheme, in comparison with MMG-based measurement schemes, provides greater accuracy.

This scheme has a number of disadvantages: the scheme does not allow to determine the direction of rotation, and the sensitivity only to the amplitude of angular velocity of the roll; the circuit has significantly less accuracy with small values of angular velocity of the roll (300 ... 1000 deg/s) compared with MMG measurement schemes. In this regard, this measurement scheme must be combined with a MMG-based measurement scheme that performs the function of measuring angular velocity of the roll at low angular velocities occurring at the acceleration site of the object [9].

The development of micromechanical, microprocessor systems and, above all, the development of micromechanical gyroscopes and accelerometers and the development of navigation systems with magnetometers and satellites (GLONASS / GPS) on their basis, successfully solve the problem of creating autonomous navigation control systems for 120 (122) mm projectiles from acceptable precision characteristics. That is, the accuracy of the characteristics of the projectiles of 120 (122) mm at the level of MQD 15 m and less can be achieved and with the use of integrated systems of satellite and inertial navigation with magnetometers. This allows us to develop an autonomous control system that provides continuity of navigation in conditions of intentional interference, as well as strong dynamic actions, that is, to provide solutions to the problems of increasing the noise immunity of the control equipment to various types of interference.

Expansion of the nomenclature of targets for artillery and reactive shells and effective solution of the tasks of defeating the point objectives of armored equipment (tank) in both concentration areas and on marches are possible in the case of MQD of the combat element of the cassette combat unit no more than 0.3 ... 0.5 m and the precision of the projectile (missile) withdrawal with such a combat element in the area of targets with MQD is not more than 100 ... 150 m.

The solution of such problems is possible with the use of a combined control system that includes an autonomous system of angular stabilization, due to the increased accuracy of delivery of combat elements and the self-guiding of combat elements to the target in the downstream part of the passive section of the trajectory.

Thus, as shown by the analysis of possible schemes for the construction of a control system for 120 (122) mm artillery shells and RSZV systems, the increase in precision characteristics of projectiles can be achieved by the use of a wide class of control systems. At the same time, it is possible to ensure the requirements for high precision shells with MQD from 15 to 100 m. Creation of guided missiles with integrated navigation system (on MEMS technologies) will allow solving small artillery problems RSZV of small caliber at a qualitatively new level while simultaneously reducing the material resources used in the preparation and execution of typical combat missions.

LIST OF USED SOURCES

1. Dudka V.D., Chukov A.N., Shmaarkov A.N. High-precision ammunition of different purpose. Tula: Publishing house of TulGU, 2002. 292 p.
2. Makarovets N.A., Ustinov L.A., Avotyn B.A. Jet rocket systems and their effectiveness. Tula: Publishing house TulGU, 2005. 293 p.
3. Matveev V.V., Shvedov A.P., Seregin S.I. Algorithm of orientation for a rotating flying vehicle / Mechatronics, automation, control. 2012. №9. Pp. 5-9.
4. Matveev V.V. Investigation of errors of free-form inertial navigation system of high-precision aircraft / V.V. Matveyev // Izvestiya Tula State University. Technical sciences. Issue 12. Ch. 1. Tula: Publishing house of TulGU, 2012. P. 165-173.
5. On-board gyro devices rotating on the flying vehicles / V.D. Dudka, V.I. Babichev, V.Ya. Filimonov, V.V. Kirilin, V.I. Gorin, V.Ya. Raspopov, D.M. Malyutin // Gyroscopy and Navigation. 2007.№1 (56). Pp. 36-47.
6. Gorin V.I., Raspopov V.Ya. Scientific bases of design of gyro devices with pulsed gyro motors // Defense technologies. 1995. №6. Pp. 44-50.
7. Gorin V.I., Raspopov V.Ya. Gyrocoordinators of rotating on the roll of rockets/ edited by B.Ya. Raspopov M.: Scientific-Technical Center «Informtekhnika», 1996. 151 p.
8. IEEE Std 1431-2994 Standard Specification Format Guide and Test for Coriolis Vibratory Gyros.
9. Raspopov V.Ya. Microsystem avionics: study. allowance Tula: «Grif and K», 2010. 248 p.

Стаття надійшла до редколегії 12.10.2018

Рецензент С. В. Лапицький, д-р техн. наук, проф.
(Центральний науково-дослідний інститут озброєння
та військової техніки Збройних Сил України)