EDUCATION AND SCIENCE MINISTRY OF UKRAINE
NATIONAL AVIATION UNIVERSITY
DEPARTMENT OF AVIATION COMPUTER INTEGRATED COMPLEXES

ADMIT TO DEFENSE
Head of department
Viktor M. Sineglazov
"21" 11 2022

MASTER'S THESIS

(EXPLANATORY NOTE)

GRADUATE OF EDUCATION AND QUALIFICATION LEVEL "MASTER"

THEME: Automatic Control System of an Unmanned Aerial Vehicle with a Variable Structure

Executor: **Maksymchuk M.V.**

Supervisor: **Ph.D., Professor Filyashkin M.K.**

Advisor on environmental protection: **Ph.D., Associate Professor Iavniuk A.A.**

Advisor on labor protection: **Senior Lecturer Kozlitin O.O.**

Norms inspector: **Ph.D., Professor Filyashkin M.K.**

Kyiv 2022

МІНІСТЕРСТВО ОСВІТИ І НАУКИ УКРАЇНИ
НАЦІОНАЛЬНИЙ АВІАЦІЙНИЙ УНІВЕРСИТЕТ
КАФЕДРА АВІАЦІЙНИХ КОМП'ЮТЕРНО-ІНТЕГРОВАНИХ КОМПЛЕКСІВ

ДОПУСТИТИ ДО ЗАХИСТУ
Завідувач кафедри
В.М. Синєглазов
"21" 11 2022 р.

ДИПЛОМНА РОБОТА
(ПОЯСНЮВАЛЬНА ЗАПИСКА)

ВИПУСКНИКА ОСВІТНЬО-КВАЛІФІКАЦІЙНОГО РІВНЯ "МАГІСТР"

Тема: Система автоматичного управління безпілотного літального апарата зі змінною структурою

Виконавець: Максимчук М.В.

Керівник: к.т.н., професор Філяшкін М.К.

Консультант з екологічної безпеки: к.т.н., доцент Явнюк А.А.

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Нормоконтролер: к.т.н., професор Філяшкін М.

Київ 2022

NATIONAL AVIATION UNIVERSITY

Faculty of aeronavigation, electronics and telecommunications

Department of Aviation Computer Integrated Complexes

Educational level: master

Specialty 151 " Automation and computer-integrated technologies"

Educational and professional program "Computer-integrated technological processes and production"

APPROVED BY

Head of department

Victor M. Sineglazov

"21" 11 2022

Graduate Student's Diploma Thesis Assignment

Maksymchuk Mykhailo Viktorovych

1. The thesis title: «Automatic Control System of an Unmanned Aerial Vehicle with a Variable Structure».

2.The thesis to be completed between: from 19.08.2022 to 15.11.2022.

3. Output data for the thesis: structural diagrams of control circuits, UAV structural diagram, ISNS diagrams, Matlab/Simulink programming environment.

4. The content of the explanatory note (the list of problems to be considered): 1. Analysis of information support for the flight of unmanned aerial vehicles (UAVs); 2. Analysis of the UAV design; 3. Analysis of existing flight control circuits by route; 4. Development and research of UAV lateral movement control circuits; 5. Development and research of flight height control circuits based on the normal overload control circuit; 6. Development and research of flight control circuits by course method.

5. List of compulsory graphic material: 1. Structural diagrams of UAV information and measurement complexes. 2. UAV structural diagram; 3. Structural diagrams of existing altitude and course control circuits; 4. Control laws and structural diagram of the flight height control circuit based on the normal overload circuit; 5. Control laws and a structural diagram of the flight control circuit by course method; 6. Research results of synthesized control circuits.

6. Planned schedule:

№	Task	Execution term	Execution mark
1	Analysis of the relevance of the problem	22.08.2022-26.08.2022	Done
2	Analysis of characteristics of unmanned aerial vehicles and their application	26.08.2022-02.09.2022	Done
3	Research of information support of control systems of unmanned aerial vehicles	02.09.2022-16.09.2022	Done
4	Research of inertial navigation systems, which are part of the integrated navigation complex	16.09.2022-23.09.2022	Done
5	Development and research of altitude control circuits based on the normal overload control circuit	23.09.2022-07.10.2022	Done
6	Development and research of flight control contours by course method	07.10.2022-21.10.2022	Done
7	Modeling of UAV movement control contours in space	21.10.2022-04.11.2022	Done
8	Conclusions on the work and preparation of the presentation and handout	04.11.2022-15.11.2022	Done

7. Special chapters' advisors

Chapter	Advisor (position, name)	Date, signature	
		Assignment issue date	Assignment accepted
Labor protection	Senior lecturer, Kozlitin O. O.	[signature]	[signature]
Environmental protection	Ph.D, Associate Professor, Iavniuk A.A.	[signature]	[signature]

8. Date of task receiving: 22.08.2022

Diploma thesis supervisor: ____________ Mykola K. Filyashkin
(signature)

Issued task accepted: ____________ Mykhailo V. Maksymchuk
(signature)

НАЦІОНАЛЬНИЙ АВІАЦІЙНИЙ УНІВЕРСИТЕТ

Факультет аеронавігації, електроніки та телекомунікацій
Кафедра авіаційних комп'ютерно - інтегрованих комплексів

Освітній ступінь: магістр

Спеціальність 151 "Автоматизація та комп'ютерно-інтегровані технології"

Освітньо-професійна програма "Комп'ютерно-інтегровані технологічні процеси і виробництва"

ЗАТВЕРДЖУЮ

Завідувач кафедри

Синєглазов В.М.

"21" 11 2022 р.

ЗАВДАННЯ
на виконання дипломної роботи студента

Максимчука Михайла Вікторовича

1. Тема роботи: «Система автоматичного управління безпілотного літального апарата зі змінною структурою».
2. Термін виконання роботи: з 19.08.2022р. до 15.11.2022р.
3. Вихідні дані до проекту (роботи): структурні схеми контурів управління, структурна схема БПЛА, схеми ІСНС, середовище програмування Matlab/Simulink.
4. Зміст пояснювальної записки (перелік питань, що підлягають розробці): 1. Аналіз інформаційного забезпечення польоту безпілотних літальних апаратів (БПЛА); 2. Аналіз конструкції БПЛА; 3. Аналіз існуючих контурів управління польотом за маршрутом; 4. Розробка та дослідження контурів управління боковим рухом БПЛА; 5. Розробка та дослідження контурів управління висотою польоту на основі контуру управління нормальним перевантаженням; 6. Розробка та дослідження контурів управління польотом за маршрутом курсовим методом.
5. Перелік обов'язкового графічного матеріалу: 1. Структурні схеми інформаційно-вимірювальних комплексів БПЛА. 2. Структурна схема БПЛА; 3. Структурні схеми існуючих контурів управління висотою та курсом; 4. Закони управління та структурна схема контуру управляння висотою польоту на основі контуру нормального перевантаження; 5. Закони управління та структурна схема контуру управління польотом за маршрутом курсовим методом; 6. Результати досліджень синтезованих контурів управління.

6. Календарний план-графік

№ п/п	Завдання	Термін виконання	Відмітка про виконання
1	Аналіз актуальності проблеми	22.08.2022-26.08.2022	Виконано
2	Аналіз характеристик безпілотних літальних апаратів та їх застосування	26.08.2022-02.09.2022	Виконано
3	Дослідження інформаційного забезпечення систем управління безпілотними літальними апаратами	02.09.2022-16.09.2022	Виконано
4	Дослідження інерціальних навігаційних систем, що входять до складу інтегрованого навігаційного комплексу	16.09.2022-23.09.2022	Виконано
5	Розробка та дослідження контурів управління висотою польоту на основі контуру управління нормальним перевантаженням	23.09.2022-07.10.2022	Виконано
6	Розробка та дослідження контурів управління польотом за маршрутом курсовим методом	07.10.2022-21.10.2022	Виконано
7	Моделювання контурів управління рухом БПЛА в просторі	21.10.2022-04.11.2022	Виконано
8	Висновки по роботі та підготовка презентації і роздаткового матеріалу	04.11.2022-15.11.2022	Виконано

7. Консультанти зі спеціальних розділів

Розділ	Консультант (посада, П. І. Б.)	Дата, підпис	
		Завдання видав	Завдання прийняв
Охорона праці	Старший викладач, Козлітін О.О,	[підпис]	[підпис]
Охорона навколишнього середовища	к.б.н., доцент, Явнюк А.А.	[підпис]	[підпис]

8. Дата видачі завдання 22.08.2022

Керівник: ______________________ Філяшкін М.К.
(підпис)

Завдання прийняв до виконання: ______________________ Максимчук М.В.
(підпис)

РЕФЕРАТ

Пояснювальна записка до дипломної роботи «Система автоматичного управління безпілотного літального апарата зі змінною структурою»:

ст., рис., табл., графіків, літературних джерела.

Об'єкт дослідження: Система автоматичного керування рухом безпілотного літального апарату.

Методи дослідження: Проведення практичних експериментів, обробка літературних джерел, пакет прикладних програм MATLAB/Simulink.

Мета роботи: Розробити контури управління для забезпечення безпечного польоту розвідувального БПЛА при попаданні в зону дії активних радіозавад і його безпечне повернення в точку старту.

Для досягнення цієї мети необхідно розв'язати наступні завдання:

– огляд предметної області та аналіз існуючих систем керування;

– розробити структурну схему системи керування БПЛА;

– синтезувати та дослідити контур управління висотою польоту на основі нормального перевантаження;

– синтезувати та дослідити контур управління польотом за маршрутом курсовим методом;

– провести моделювання системи керування БПЛА на базі математичної моделі в графічному середовищі MATLAB/Simulink;

Матеріали дипломного проекту можуть бути використані для удосконалення або подальшого розвитку систем керування безпілотних літальних апаратів.

БЕЗПІЛОТНИЙ ЛІТАЛЬНИЙ АПАРАТ, АВТОМАТИЧНА СИСТЕМА КЕРУВАННЯ, КОНТУР УПРАВЛІННЯ, ІНЕРЦІАЛЬНО-СУПУТНИКОВА НАВІГАЦІЙНА СИСТЕМА.

ABSTRACT

Explanatory note to the thesis " Automatic Control System of an Unmanned Aerial Vehicle with a Variable Structure": p., figures, tables, graph, literary resources.

The object of research: Automatic control system of the movement of an unmanned aerial vehicle.

Methods of research: Conducting practical experiments, processing literary sources, a package of MATLAB/Simulink application programs.

The purpose of the work: Develop control circuits to ensure the safe flight of a reconnaissance UAV when it enters the area of active radio interference and its safe return to the starting point.

To achieve this goal, the following tasks must be solved:

– review of the subject area and analysis of existing control systems;

– develop a structural diagram of the UAV control system;

– synthesize and research an altitude control loop based on normal overload;

– synthesize and research the flight control loop according to the course method;

– conduct modeling of the UAV control system based on a mathematical model in the MATLAB/Simulink graphical environment;

The materials of the diploma project can be used for improvement or further development of control systems of unmanned aerial vehicles.

UNMANNED AERIAL VEHICLE, AUTOMATIC CONTROL SYSTEM, CONTROL LOOP, INERTIAL SATELLITE NAVIGATION SYSTEM.

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GLOSSARY

UAV – Unmanned Aerial Vehicle.

SNS – Satellite Navigation System.

SRNS – Satellite Radio Navigation System.

INS – Inertial Navigation System.

SSC – Subsystem of Spacecraft.

SCM – Subsystem of Control and Management.

CMC – Command and Measurement Complex.

ADC – Analog-to-Digital Converter.

APU – Auxiliary Power Unit.

PML – Phase Monitoring Loop.

DML – Delay Monitoring Loop.

GPQR – Generator of in-Phase and Quadrature Readings.

PINS – Platformless Inertial Navigation System.

KFss – Kalman Filter of the satellite system.

AMNS – Aeromagnetic Navigation System.

INTRODUCTION

The existing approach to information support for the flight of small and miniature unmanned aerial vehicles (UAVs) is based on the use of inertial satellite navigation systems as the main source of information about flight and navigation parameters.

However, with this approach, there is a threat of loss of flight information support in the presence of strong radio interference. At the same time, the loss of information about the parameters of the angular orientation, in particular about the angles of roll and pitch, can lead to the loss of the UAV itself. And in the absence of navigational information from the SNS, only a rough micromechanical INS is not able to ensure that the UAV leaves the zone of radio interference and returns to the starting point.

A number of alternative methods for measuring roll and pitch angles, such as pyrometric or magnetometry methods, can be used to store attitude information. Another solution is the joint processing of signals from accelerometers and PINS gyroscopes. For this purpose, various variants of algorithms for complexing this information are being developed, for example, the so-called complementary filters or Kalman filtering algorithms.

To solve navigation problems in the absence of information from the SNS, the UAV navigation system is usually switched to the aerometric dead reckoning mode. Other approaches to solving navigation problems are also proposed, for example, visual odometry based on information from the onboard UAV webcam.

Thus, research aimed at improving the reliability of UAV flight information support, reducing the risk of its loss, is very relevant.

The paper proposes, when flying a UAV in the area of active radio interference, by changing the structures of the automatic control loops, to abandon the use of unreliable information that is not obtained by direct autonomous measurement and can lead to the loss of the UAV. For example, if information about the roll and pitch angles is obtained by estimating the state vector, then failures in the operation of the SNS will almost instantly lead to a distortion of this information. Distortions of flight information led to unacceptable deviations of the UAV and, as a result, to its loss.

Thus, the problem statement can be formulated as follows: to develop algorithms for the UAV automatic control loops at the stage of leaving the zone of active radio interference and conduct their comprehensive research.

CHAPTER 1. REVIEW OF LITERATURE AND RESEARCH OF THE AIRCRAFT CONTROL PROCESS, ANALYSIS OF EXISTING CONTROL SYSTEMS

1.1 Analysis of the characteristics of unmanned aerial vehicles and their application

According to the definition approved by the ICAO Assembly [1], "An unmanned aerial vehicle (drone) is an unmanned aircraft that flies without an aircraft commander on board and is either fully remotely controlled from another location on the ground, from another aircraft, from space, or programmed and fully autonomous."

Aviation experts distinguish two main types of aircraft, in addition to military missiles, which fly without airborne pilots:

- Remote controlled;
- Programmed and operated by navigation systems;

For the first time, civilian use of drones was announced by Amazon [2] for the delivery of consumer goods in 2013. After that, the market began to develop rapidly, opening up new areas of commercial and private use. In addition to the manufacturers of unmanned aerial vehicles (UAVs) themselves, distributors of such devices, manufacturers of components, optics and computer vision systems, software, companies of mapping services and aerial photography, the agricultural sector, a wide range of government services (police, ambulance, firefighters, emergency services), insurance and investment companies and others. Also, now with the help of drones, the assessment of air pollution and radioactivity is being carried out, objects are being protected, there is also an idea of using drones to deliver medicines and medical devices to the scene of an incident, extinguishers for extinguishing, and even the delivery of ammunition.

Unmanned aerial vehicles are difficult to classify as they have very different characteristics. This diversity comes from the abundance of UAV configurations and components. Manufacturers are not yet limited by any standards. As a result, today there are no requirements from aviation regulators on how the UAV should be equipped.

UAVs [3,4] differ in size, flight range, flight speed, functionality, level of autonomy, flight duration and other characteristics.

Conventionally, all drones can be divided into 4 groups:

- Micro. Such UAVs weigh less than 10 kg, the maximum time spent in the air is 60 minutes. Flight altitude - 1 kilometer.
- Mini. The weight of these devices reaches 50 kg, the residence time in the air reaches 5 hours. The flight altitude varies from 3 to 5 kilometers.
- Midi. Unmanned aerial vehicles weighing up to 1 ton, are designed for 15 hours of flight. Such UAVs rise to a height of up to 10 kilometers.
- Heavy drones. Their weight exceeds a ton, devices for long-distance flights lasting more than a day have been developed. They can travel at an altitude of 20 kilometers.

According to the variety of designs, there are 4 main types of unmanned aerial vehicles:

- Multi-rotor - multi-rotor drones;
- Fixed wing drone;
- Single rotor drone - unmanned helicopter;
- Hybrid drones.

Multi-rotor drones are the most common types of drones used by professionals and amateurs alike. Such a drone is a flying platform with 3, 4, 6, 8, 12 brushless motors with propellers. So a drone with four motors is called a Quadcopter, with six - Hexacopter, with eight - Octocopter. In flight, the drone keeps a horizontal position relative to the surface of the earth and can hover over a certain place, move left, right, forward, backward, up and down, as well as rotate around its axis. All actions are performed by changing the thrust on each motor.

The market segment for such devices is diverse, including multi-rotor drones for professional use, such as aerial photography, the price of which can range from $ 500 to $ 3000. But there are many hobby models such as amateur drone racing or leisure flying, ranging in price from $ 50 to $ 400. Of all types of drones, multicopter drones are the easiest to make and the cheapest.

The main problem with multicopters is that they have to spend a huge part of their energy fighting gravity and stabilizing the craft in the air. Currently, most multi-rotor drones are capable of flying for only 20 to 30 minutes with minimal payload such as a video camera.

Fixed-wing drones are completely different in design from multi-rotor drones. They use a "wing" to fly, and create lift, just like conventional airplanes do. These drones cannot hover in place in the air while fighting gravity. Instead, they can move forward on a given course for as long as their energy source allows.

Most fixed-wing drones [5] have an average flight time of a couple of hours. Gas powered drones can fly for up to 16 hours or more. With their longer flight times and fuel efficiency, fixed-wing drones are ideal for long-range operations (be it mapping or surveillance). But they cannot be used for aerial photography, where the drone must remain stationary in the air for a certain period of time.

Other disadvantages of fixed-wing drones are the higher costs of training personnel in the flight control skills. It is not easy to fly a fixed-wing drone into the air. To launch and lift a fixed-wing drone into the air, either a dedicated "runway" or a catapult launcher is required. To safely land the craft back on the ground, you will also need an airstrip, parachute, or net.

Single rotor drones are very similar in design and to real helicopters. Unlike a multi-rotor drone, a single-rotor drone has one large lead rotor plus a small rotor on the tail to control the course. Single rotor drones are much more efficient than multi-rotor versions. They have a longer flight time and can even be powered by internal combustion engines.

In aerodynamics, the fewer the number of propellers, the less the total rotation of the object. And this is the main reason why quadcopters (4 propellers) are more stable than octopters (8 propellers). In this sense, single rotor drones are much more efficient than multi rotor drones.

But there are also disadvantages to single rotor drones. These machines, due to their more complex design, have a high cost and operating costs. They also require special training of personnel for management. Large rotor blades are dangerous. Accidents of fatal injuries were recorded by the propeller of a radio-controlled helicopter. For example, multi-rotor drones have never participated in fatal accidents, although it is quite possible to get a scar on the human body from the propeller of a multi-rotor drones.

Hybrid versions combine the advantages of fixed-wing models such as higher flight times with the advantages of propeller-based models - the ability to fly. Hybrid aircraft designs have been in development since the 1960s but have had little success. However, with the advent of new generation sensors (gyroscopes and accelerometers), the hybrid design has received a new life and direction of development.

The design of the unmanned vehicle [6] includes a satellite navigator and a programmable module. If the UAV is used to receive, store and transmit information to the operator's console, a memory card and a transmitter are additionally installed in it.

The design and functionality will vary depending on the purpose of the device. There are drone models that are able to take human commands and respond to them. In such devices, special command receiver modules are installed.

For day-to-day vessels, it is characteristic є wide availability of automatic control systems (ACS) practically in all modes and stages of use. Without such systems, it is unwisely effective to check the aviation technology for finding the simplest tasks of transportation.

1.2 Description of control systems

An analysis of literary sources shows how on the current day the main UAV will be stuck with a remote flight [7]. Victory of such lithic devices has a number of peculiarities, connected with the permanent stitches of the operator behind the drone's camp in the open space, the transfer of possibilities with the cross-codes and the free supply of high-quality signals to the drive drivers. This requires appropriate qualification from the operator. This approach has significant disadvantages:

- the area of the storage of the aircraft was surrounded, caused of the need to receive a call from the operator's post;
- the foldability of the control is due to the direct deposition between the operator and the crash of the drone, which can be brought up to the operator;
- folding of adequate control based on telemetry data.

More promising is UAV control system due to the availability of autonomous navigation annexes and the transfer code value. For any reason, the drone can move in space independently, directly from the operator.

The autonomous mode of the drone is stored from the decile of the main stages [8], such as being displayed before the next fuel injection, and coming from the onboard self-propelled gun:

1. takeoff from some surface;
2. moving the UAV in the horizontal plane to a given point in space;
3. transition to the freeze mode, which allows for reconnaissance, video recording and (or) perform the necessary measurements;

4. return to the starting point or any other set point and landing.

Obviously, when designing an onboard automatic autonomous flight control system, it is necessary to solve the problem of determining the real coordinates of the drone by processing data from sensors, matching them with the specified in memory, finding control effects on deviations of real coordinates from the specified.

Of particular interest is the UAV stabilization mode, which is characterized by the ability of the drone to hang in the air at a given height and monitor the environment. This mode is convenient to carry out autonomously using the onboard ACS drone. An accelerometer, gyroscope and barometer are installed in the flight controller control system for this function. At the same time, today even the best models of drones have low accuracy of hanging on the point. Deviation in height reaches ± 0.5 m; and in the horizontal plane ± 1.5 m. Development of new algorithms of autonomous management allows to solve the set task more qualitatively.

Recently, the methods of intelligent control of UAVs are becoming more widespread. However, to date, in most cases, the implementation of such control in nondeterministic conditions has a drawback, which is associated with the lack of ability of intelligent control systems to adapt to dynamic conditions. Independent operation of the drone in unpredictable conditions is possible with the further development of intelligent control systems. In this case, control by the operator can be carried out at a higher level - at the level of goal setting. However, such methods of controlling the movement of UAVs are poorly developed.

The aircraft, which is controlled at the level of goal setting, must move in a non-deterministic environment, which is characterized by a previously unknown location of obstacles and targets, as well as their mobility. In such conditions, the independent movement of the robot determines the need for dynamic analysis of the situation in the operating environment. Based on the results of such analysis, carried out in the General case with the help of sensory information and the target setting of the operator, the UAV control system must navigate and control its movement [9].

Accordingly, there are three types of architectures of motion control systems for unmanned aerial vehicles:

1. architecture based on the decomposition of information processing functions in the process of (Sensor - Model - Plan - Act, SMPA);
2. reactive (reflex) architecture based on the strategy of purposeful behavior of the UAV, which is produced on the basis of sensor information (sensor-based action);
3. hybrid architecture based on a combination of two previous types of architectures.

A typical structural and functional diagram of the SMPA-drone motion control system is presented in Figure 1.1.

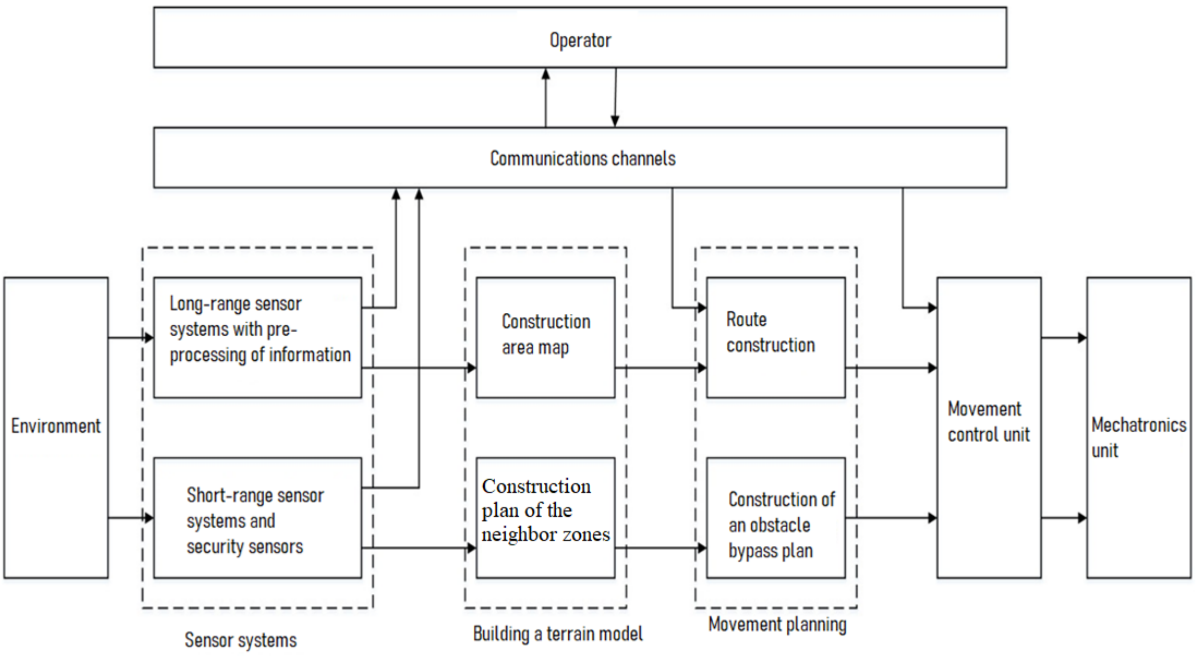

Figure 1.1 - Typical structural and functional diagram of the SMPA-motion control system for unmanned aerial vehicles

This system controls the movement of the drone by modeling the environment, localization in it, as well as planning, correction and development of trajectories.

Environmental modeling is carried out on the basis of sensory and other information coming from various sources. The environmental model should describe in the dynamics of the location of the drone, obstacles and targets.

The task of self-localization of UAVs is closely related to the task of modeling the workspace, because their solutions are interdependent, ie the quality of the solution of one determines the quality of the solution of the other. To solve this problem, methods of path calculus, integral and sensory localization are used. The path calculation method involves the analysis of the accumulated error and in most cases is used in conjunction with the sensory method to eliminate it, as well as to match the characteristics or guidelines in the work environment. The method of integrated navigation involves the implementation of global positioning (GPS) and laser scanning of the environment. When modeling the working space of the UAV distinguish geometric and topological localization. Geometric localization determines the position and orientation of the drone, topological - its relationship with the operating environment.

To date, there are three main strategies for localization computing:

1. periodic combination of a local model of the environment with a given a priori map;
2. determining the position on the basis of a priori well-known benchmarks;
3. selection of environmental characteristics and assessment of their positions relative to the drone, followed by determination of its resulting movement.

UAV trajectory planning can be based on the following approaches:

1. methods based on the road map, where visibility graphs are used;
2. representation of the map of the environment in the form of a field in a cell, which involves the implementation of Delaunay triangulation, as well as division into square and hexagonal segments, which can be implemented models

of probabilistic passage, models with information accumulation, etc .;

3. movement in virtual information fields, which involves the use of heuristic algorithms, as well as algorithms based on the method of potentials;

4. methods of planning the behavior of the movement, where the formed plan is a sequence of behavioral acts, the transition between which is carried out under certain conditions.

In the general case, there are global and local planning. Global planning is based on a terrain map (for example, using GPS, long-range sensor systems), local - based on signals from short-range sensor systems and security sensors received in real time.

1.3 Analysis of information support of control systems of unmanned aerial vehicles

The current approach to providing flight information for small and miniature UAVs is based on the use of inertial-satellite navigation systems as the main source of information about aerobatic and navigation parameters of the flight. The main problem of this approach to the information support of the UAV flight is the problem of the reliability of the navigation support. The low reliability of information support can lead to the loss of the UAV itself, in particular, in the case of loss of information from the satellite navigation system, for example, due to difficult radio technical conditions for receiving signals from a satellite constellation or due to the installation of special radio technical interference by the enemy, since a coarse micromechanical INS [10] is not able to provide UAVs with pilotage and navigation information of the necessary accuracy even at small time intervals. We will analyze the components of the existing inertial-satellite navigation systems.

Today, it makes sense to consider only two satellite navigation systems: GPS (Global Positioning System) and GLONASS (Global Navigation Satellite System) [11].

Twenty-four satellites of the GPS system are in 12-hour orbits (in 6 planes, 4 satellites in each of them), with an altitude of 20,146 km and an orbital inclination equal to 55°. Thus, at any point on the globe within line of sight, there are at least four satellites in a configuration that is favorable for location determination.

The system is based on calculating the distance from the user to the satellite based on the time measured between the transmission of the signal by the satellite and the reception of the signal by the user.

The Global Navigation Satellite System (GLONASS) is the sum of unique technologies, the fruit of many years of work by Russian designers and scientists. It consists of 24 satellites that are located at specific points in high orbits and continuously send special navigation signals in the direction of the Earth. Each person or vehicle that uses a special device for receiving and processing these signals can determine their own coordinates and speed of movement with high accuracy at any point on Earth and in the Earth's orbit, and also tie it to the exact time.

Three main subsystems function as part of a modern satellite radio navigation system (SRNS) such as GLONASS and GPS:

1. Subsystem of spacecraft (SSC), consisting of navigation satellites (NS, network of navigation satellites - space segment). SSC of SRNS consists of a fixed number of navigation satellites. The main functions of NS are the formation and emission of radio signals necessary for the navigational determination of consumers MRNS, control of on-board satellite systems by the control and management subsystem MRNS. The appropriate characteristics of NS signals and their processing methods allow for high-precision navigation measurements.

2. Subsystem of control and management (SCM) (ground command and measurement complex (CMC)) - control segment. SCM is a complex of ground facilities (CMC), which provide observation and control over the trajectories of

NS motion, the quality of the functioning of their equipment, control of its operation modes and parameters of satellite radio signals, the composition, volume and discreteness of navigational information transmitted from satellites, etc.

3. Consumer equipment (CE) SRNS is reception indicators (RI) – consumer segment.

Consumer equipment is designed to determine spatial coordinates, velocity vector, time and other navigation parameters as a result of receiving and processing radio signals from many navigation satellites (NS).

Signals from NS located in the radio visibility zone are received at the RI input. Since it is necessary to measure pseudo-ranges and pseudo-velocities relative to at least four NS to solve the navigation problem, the RIs must be multi-channel (more than 24 in combined GLONASS and GPS).

Modern RIs are analog-digital systems that perform analog and digital signal processing. The transition to digital processing is carried out at one of the intermediate frequencies, while there is a tendency to increase this intermediate frequency.

The basis of a typical version of RI is two structurally separate blocks: antenna unit (AU) and reception computer (RC), which are designed to receive and process navigation signals from satellites in order to determine the information needed by consumers (space-time coordinates, direction and speed, etc.).

In the antenna unit (Fig. 1.2), the set of NS signals received by the antenna is pre-amplified and filtered over the entire carrier frequency band (FB) in pre-amplifier (PA) with bandpass filter (BF) [12].

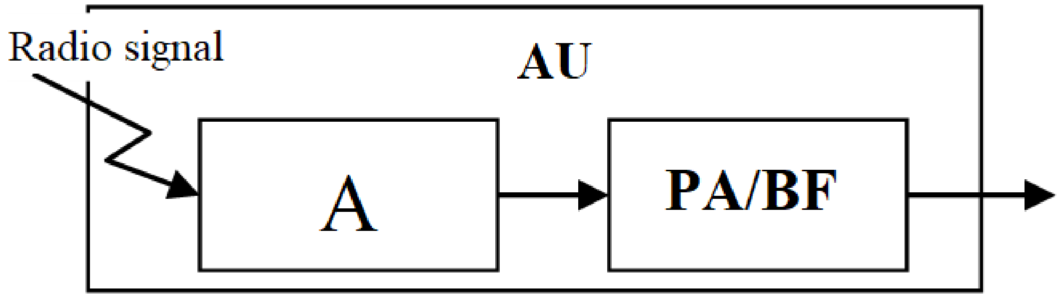

Fig. 1.2 Structure diagram of Antenna Unit

The receiving computer is made in the form of a block in which the modules of secondary power sources and receiving correlator boards, navigation computer and interface device are located (Fig. 1.3). The input of the software is connected to the output of the antenna unit through the feeder line. In analog receiver (AR) signals are amplified, filtered and transferred from the carrier frequency to an intermediate one (frequency reduction). In analog-to-digital converter (ADC) the analog signal will be converted into digital form.

In correlator (COR) in-phase and quadrature readings are formed in digital form, which is the basis of the work of algorithms for searching for signals by delay and frequency of observing the pseudo-range, signal phase and selection of the navigation message.

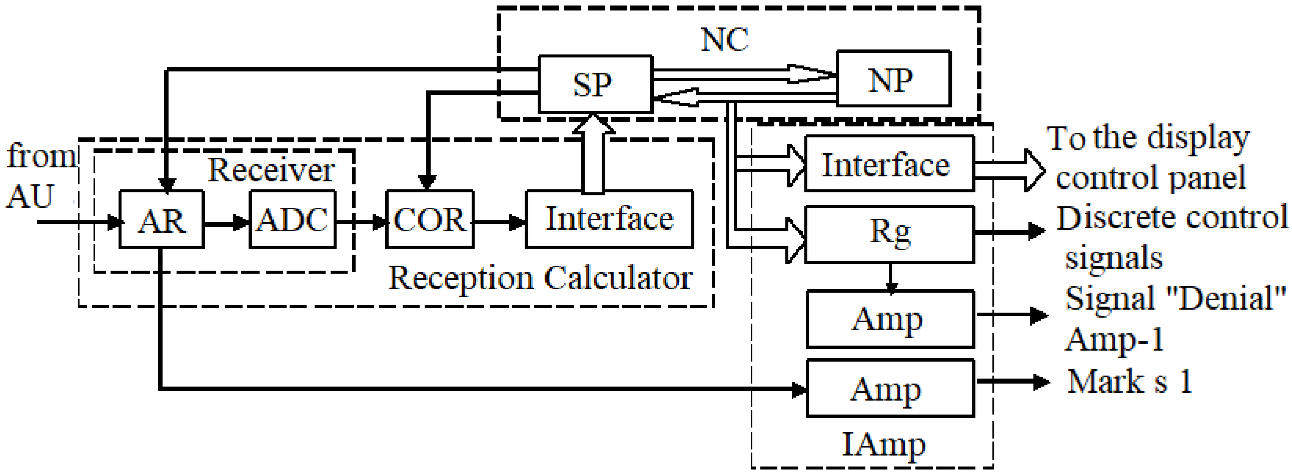

Fig. 1.3 Scheme of the receiving computer

Navigation computer (NC) is a digital processor that implements the computing process and control of RI work. It is convenient to present the navigation computer in the form of a signal processor (SP), which implements algorithms for the primary processing of quadrature components, and a navigation processor (NP), which implements low-frequency processing algorithms, i.e., a solution to the navigation problem.

Delay is measured in the received radio signal τ or Doppler frequency shift $f_{доп}$, which are radio navigation parameters, and the corresponding distance to the object $D = c\tau$ and the radial velocity of convergence $V_p = f_{доп}\lambda$ serve as navigation parameters (c – speed of light; λ - the wavelength of a radio signal).

The spatial position of the consumer is determined in the RI in two stages: first, the current coordinates of the satellites and the primary navigation parameters (range, its derivatives, etc.) are determined in relation to the relevant NS, and then the secondary ones are calculated - the geographical latitude, longitude, height of the consumer, etc.

The consumer's velocity vector is calculated by processing the results of measurements of Doppler shifts of the frequency of the NS signals, taking into account the known velocity vector of the satellite.

The ID interface device is designed to ensure the interaction of the reception indicator with external devices, such as, for example, as control and display panel (CDP). In addition, the ID includes two amplifiers (Amp), which form a sign of failure of the RI and discrete control signals, as well as an 8-bit register (Br), which accepts discrete control signals. This register is readable by the MP. The latter, depending on the information in the register, chooses one or another mode of operation.

Thus, the main operation performed in the SNS with the help of the space segment, the control segment and the consumer segment is the determination of the spatial coordinates of the location of consumers and time, i.e. spatio-temporal coordinates (STC). As it was shown, this operation is carried out in accordance with the concept of independent navigation, which involves the calculation of the desired navigation parameters directly in the consumer's equipment. Within the framework of this concept in SRNS the chosen positional method of determining the location of consumers based on non-requested (passive) long-range measurements based on the signals of several navigation artificial satellites of the Earth with known coordinates.

The high accuracy of determining the location of consumers is due to many factors, including the relative location of satellites and the parameters of their navigation signals. The structure of the space segment provides the consumer with constant visibility of the required number of satellites.

The use of SNS in the interests of location and navigation of moving objects, as well as in solving special tasks (surveillance, aerial photography, search for minerals, search and rescue of vehicles and people suffering misfortune) makes high demands. The requirements for accuracy characteristics, such as the root mean square error (RMS) of the determination of navigation parameters, indicators of the reliability of navigation support, etc., are as follows:

- availability (readiness), the measure of which is the probability of the SRNS working capacity before the performance of a particular task and in the process of its performance. Numerical values of availability are 0,95;...;0,997;

- integrity, the measure of which is the probability of detecting a failure over time, equal to the given or less. Integrity requirements for scheduled flights are 0,999;

- continuity of service, the measure of which is the probability of system operability during the most critical periods of time. At the stages of the approach, the requirements for continuity of service are made $1 \cdot 10^{-5}$ …... $1 \cdot 10^{-4}$ for time intervals from 15 to 150 s.

The main navigational parameters defined in SRNS [13] are range and radial speed. The corresponding radio navigation parameters (radio signal parameters) are signal delay τ and Doppler frequency shift $f_{доп}$, the measurement of which must be highly accurate, which is the main requirement for radio signals.

The requirements for increasing the accuracy of signal delay and Doppler frequency shift are contradictory. To increase the accuracy of the delay measurement, it is necessary to expand the signal spectrum, and to increase the accuracy of the Doppler frequency shift measurement, it is necessary to increase its duration. This contradiction is resolved when solving the problem of joint assessment τ and $f_{доп}$.

Increasing the accuracy of the joint estimates of signal delay and Doppler frequency shift can be achieved by increasing the so-called signal base – B (the product of the effective signal duration by the effective signal spectrum width), and the main requirement for radio signals in SRNS is to increase the signal base $B \gg 1$. Such signals are called noisy. It is known that the resistance to interference of a radio technical system is determined by the value of the signal base, and for most UAVs, stealth and immunity are one of the defining requirements.

Another essential requirement is the provision of multi-station access. When determining the navigation parameters, the consumer must be able to simultaneously access signals from different satellites. The problem of multi-station access is solved by temporal, frequency or code division of signals, for example, in the GPS satellite navigation system code division is used, in GLONASS SRNS - frequency division.

From the results of the analysis, it becomes obvious that there is no fundamental difference between GPS and GLONASS satellite navigation systems.

Depending on the area of use, consumer equipment (CE) has its own characteristics, therefore CE manufacturers always indicate the area of application of the corresponding sample. In addition to the main units, such as the antenna, receiver, indicator, the CE may contain auxiliary units that provide special service functions, for example, diagnostics of vehicle components, communication with the dispatch center, etc.

Table 1 provides brief information on the main CE models operating on GLONASS and GPS signals. The given information does not pretend to be complete with information about existing CE models and their characteristics, but is given to illustrate the level reached in the development and production of SRNS CEs.

Table 1 – Examples CE

The name of the equipment	Field of use	Manufacturer	Number of channels	Precision (in offline mode)		Mass, kg
				coordinates, m	speed, m/s	
„Гном-М”	Aviation		6...12	80...90	12...15	3,2
АСН-22	Aviation	РИРВ	18	25...30		0,4
НАВИС СН 3301	Aviation		14	15...20	8...10	2,4
„Интер-А”	Aviation	МКБ КОМПАС	12	25...30	10...30	3,5
А-744	Aviation	Фирма „Кодтик”	6	30...35	15...20	2

Given the fact that the satellite navigation system will work in conjunction with the inertial navigation system, it is hardly worth installing a complete set of the satellite system on board the UAV. It is enough to limit ourselves to the reception indicator and the signal processor, assuming that the algorithms for solving the navigation problem will be solved in the joint processor of the inertial-satellite navigation system.

Based on the above, as well as taking into account the conditions of use of the UAV and the requirements of the TOR, it is possible to formulate the requirements that the selected type of reception indicator of the SRNS must satisfy.

Solved problems:

– automatic, continuous, global, all-weather determination of the current 3D location coordinates, path speed vector and path angle of the UAV during operation: by the standard accuracy signal of the L1 frequency range of GLONASS; by signal 3/A-code GPS; with the joint processing of the above-mentioned signals;

– issuing the current 3D coordinates of the location of the UAV, which are components of the velocity vector and the path angle in the СК-42 or ПЗ-90 coordinate system in geographic format, as well as indications of the operating mode of the equipment;

– stable determination of navigation parameters when moving with linear accelerations and with jump-like changes in acceleration;

– the possibility of switching from the carrier antenna to the UAV antenna;

– integral assessment of the expected accuracy of determining the current coordinates of the location;

– automatic selection of the optimal GLONASS and GPS constellation in terms of expected accuracy when working in combined mode;

– automatic solution of the navigation problem in the geographic coordinate system.

Characteristics:

Accuracy of determination of navigation parameters:

– coordinates (MSD), m......…………………………..............................10

– speed, m/s......…………..…………………………..............................0,1

– altitude (MSD), m......…………………………..............................0 ÷ 15

Characteristics must be kept at:

– speed, m/s to...………….....……………..………...........................400

– maximum acceleration, g….....(depends on the UAV launch conditions)

– maximum jerk, g/s..................(depends on the UAV launch conditions)

Determination time

– cold start, min..……………....…………......................... no more than 2

– recapture time, s...3-15

– the maximum value of roll and pitch, deg….................................40-50

– coordinate recovery frequency, s^{-1}................................ no more than 1

Interface:

As rule RS-232C

Working temperature, °C...……………………...…...…..............–55 +85

Working humidity, %...98 (25°C)

The central, highly informative link of the integrated UAV navigation complex is the inertial navigation system.

1.4 Analysis of inertial navigation systems included in the integrated navigation complex

According to the method of determining the coordinates of the location of a moving object, INSs are classified as path calculation systems. They can be built according to different schemes depending on the purpose or type of the object, the tasks that this object must perform, from the choice of basic (in which the optimization problem is solved) or connected (in which the measurement and integration of velocities is carried out) coordinate system (CS), as well as from the selection of inertial sensitive elements.

The main sensors of inertial navigation systems (INS) are path calculation sensors, which are divided into two functional classes:

1. Accelerometers are designed to measure acceleration and calculate it by integrating the acceleration of its speed and the distance traveled.

2. Motion direction sensors (gyroscopes):

- rotation sensor (positional gyroscopes) - designed to determine the direction (angle of rotation and inclination of the object);

- angular speed sensors - designed to measure the angular speed of rotation.

The angular velocity sensor differs from positional gyroscopes in that its axis of rotation is clamped rather than free. When turning the platform on which the angular velocity sensor is installed, a Coriolis force occurs, the magnitude of which can be used to judge the angular velocity of the platform rotation.

Therefore, the calculation of the path and determination of the parameters of the object's movement is carried out in one of the coordinate systems related to the Earth. Inertial sensitive elements (which act as gyroscopes and accelerometers) measure the parameters of angular and translational motion in inertial space.

INSs are divided into two main classes: platform and platformless. In platform INSs, all elements are sensitive (accelerometers are placed on a gyro-stabilized platform). In the platform-less INS, the sensitive elements are placed directly on the aircraft body.

The following systems are distinguished among platform INSs:

- with a non-corrected platform;
- with a horizontal platform.

In an INS with an uncorrected platform, the platform axes and accelerometers installed on this platform do not rotate in inertial space.

INSs with a horizontal platform are divided into:

- INS with a platform free in azimuth (the platform is located relative to a point in world space - relative to a star);
- INS with an azimuth-corrected platform (the platform is stabilized relative to the meridian – “directed” to the north).

INSs are distinguished depending on the role of the calculator in determining angular and linear coordinates:

- geometric;
- semi-analytical;

- analytical.

In geometric INSs, the main element is a gyrostabilizer, which reproduces the direction of the axes of the inertial reference system, and a platform with accelerometers, whose sensitivity axes reproduce some directions in the horizon plane and the direction of the local vertical. The role of the computer in such INS is minimal and is reduced to ensuring the correction of the given position of the platform. Information about the coordinates is taken from the devices for measuring the angles of the gyro stabilizer and the platform.

Semi-analytical systems include systems with a horizontal platform. In these systems, the gyro platform with accelerometers reproduces the direction of the normal (moving) frame of reference. Information about the angles of roll, pitch, and course of the aircraft is taken from the angle measuring devices of the gyrostabilizer. The INS computer solves the problem of determining the kinematic parameters of the movement of the center of mass of the aircraft and issues signals for the correction of the gyro stabilizer.

Analytical INSs include:

- platformless INSs (PINS);
- INS with accelerometers on an uncorrected or free gyro stabilizer.

In addition to determining the kinematic parameters of the movement of the center of mass of the aircraft, the INS calculator determines the angular orientation of the normal moving coordinate system relative to the inertial one, and the angular orientation of the connected moving coordinate system relative to the normal.

Recently, more and more attention has been paid to the development of PINS, in which accelerometer sensors are rigidly connected to the aircraft body. This is especially true for miniature UAVs. Such systems include gyroscopic devices, but the main task of these devices is to provide PINS computers with information about the angular position of the aircraft, as well as about the position of the sensitivity axes of the accelerometers relative to the selected navigation coordinate system. The absence of a horizontal platform requires that the signals that are the accelerations of the aircraft be isolated from the readings of the accelerometers. At the same time, the accuracy of the specified simulation is determined by the accuracy of the computer and, of course, the accuracy of the primary navigation information sensors.

Platformless INSs include:

- accelerometers and angle sensors;
- accelerometers and angular velocity sensors;
- accelerometers.

Advantages of PINS compared to platform INSs:

1) smaller size, weight and energy consumption;
2) simplification of the mechanical part of the system;
3) no restrictions on turning angles;
4) reducing initial setup time.

Let's consider a small-sized inertial navigation system (INS), which is part of the on-board navigation and control system of the UAV. SINS is a complete inertial system in which the platformless INS algorithm is implemented, integrated with the receiver of the satellite navigation system.

A typical PINS construction scheme is presented in fig. 1.4. This option implements the algorithm of the system that works in the rotating Earth coordinate system.

PINS primary information sensors - angular velocity sensors and accelerometers are rigidly installed on the aircraft. The complex operating conditions of information sensors lead to the appearance of significant errors, therefore, it is desirable to carry out analytical compensation of meter errors in the PINS work algorithms before these signals are used to calculate the orientation parameters and to determine the components of the imaginary acceleration along the navigation axes.

A mathematical model of the meter is required to correct the readings of primary information sensors.

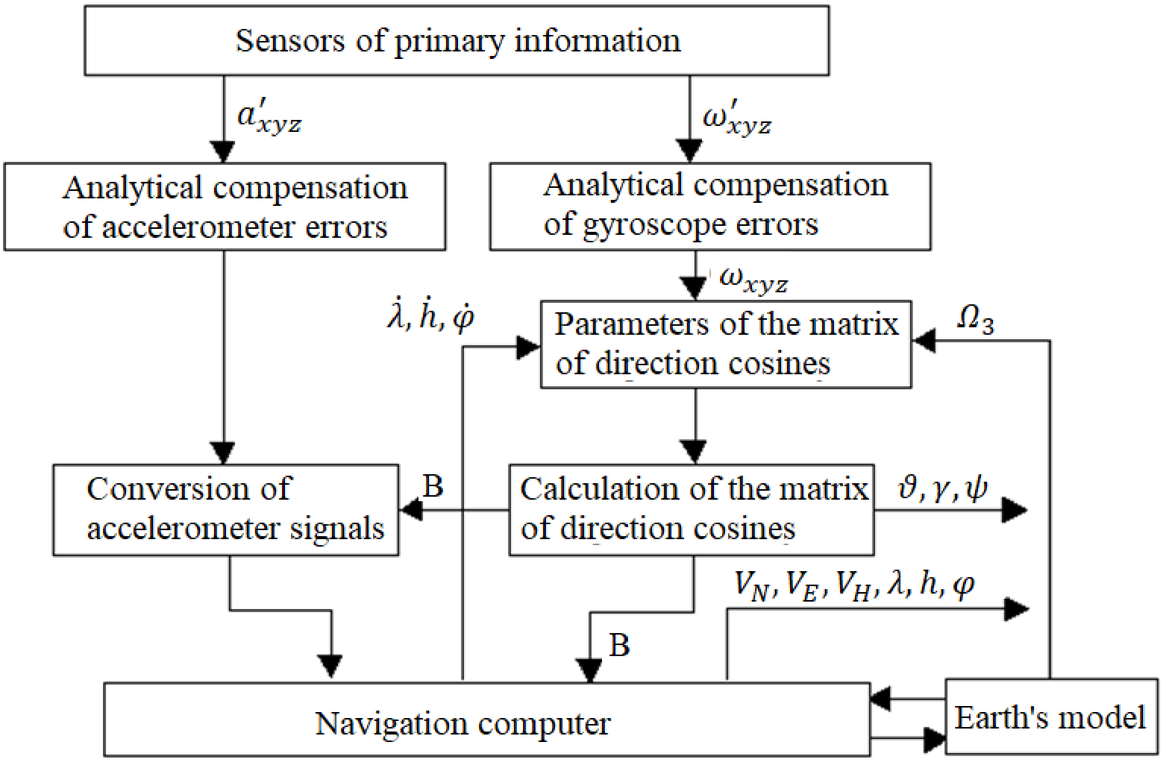

Fig. 1.4 A typical PINS construction scheme

Signals ω_{xyz} from the output of the analytical error compensator are used to calculate the parameters of the matrix of direction cosines B, which determines the relationship between the two coordinate systems. Since the matrix of direction cosines B is determined between the axes connected to the aircraft and the axes of the rotating navigation coordinate system, when calculating the parameters of the matrix B, it is necessary to involve the calculated projections of the angular velocity vector of the navigation coordinate system, which is shown in the diagram by additional links that take into account the angular velocity , which occurs when orbiting the spherical Earth $(\dot{\lambda}, \dot{h}, \dot{\phi})$, and the angular velocity of rotation of the Earth itself (Ω_3).

Transformation of components of imaginary acceleration a_{xyz} from the axes of the aircraft to the axes of the navigation coordinate system is carried out using the matrix of direction cosines B. The navigation computer solves the problems inherent in all platform systems, because at the input of this computer, projections of the imaginary acceleration on the axis of the navigation coordinate system are formed, and there is nothing fundamentally new in solving this problem there is no problem. At the output of PINS, the radius vector of the location of the aircraft, the vector of speed, as well as the orientation angles of the aircraft are formed.

It is PINS that is chosen as the central, highly informative link of the integrated UAV navigation complex.

1.5 Analysis and selection of schemes for building inertial-satellite navigation systems

Currently, there are several variants of SNS and INS complexation schemes [14]. Among them, the most popular in use are:

1. Loosely connected systems.
2. Rigidly connected systems.

In loosely connected systems, the INS should ensure long-term functioning while maintaining acceptable accuracy. Standard requirements for INS errors in this case are 1 nautical mile per hour (≈1800 km/h). Thus, the possibility of both separate functioning of INS and SRNS for a long period of time, and their joint functioning in an integrated mode is envisaged.

In the SRNS (see Fig. 1.5), the signal received by the antenna unit is a carrier frequency signal (≈1.6 GHz), amplitude-modulated by a pseudo-random signal with a duration of $\delta t \approx 1$ μsec (or 300 m equivalent code length). Input signals are demodulated and fed to the correlator.

At the same time, the generator of in-phase and quadrature readings (GPQR) of the correlator generates copies of these signals, which are shifted in time by intervals $+\delta_t, +2\delta_t, \ldots or - \delta_t, -2\delta_t, \ldots$ Delay Monitoring Loop (DML) issues command signals that delay or advance signals at the output of the correlator (see. $[+,-]$ on Fig. 1.4) until the signal of the maximum value appears at the output of the correlator, and the difference of the correlator signals at the previous and next control steps is not equal to zero. This means "capture" of the satellite signal, and the value of the resulting delay $k\delta_t$ is considered the propagation time of the signal from the satellite to the receiver. It is used to calculate the pseudorange ρ to a specific satellite.

The in-phase and quadrature components of the carrier frequency signals (I and Q, respectively, in Fig. 1.5) are fed into the carrier frequency phase monitoring circuit (PML). The arctangent of the ratio of the amplitude of the quadrature (Q) signal to the in-phase (I) is the error of the PML. This error signal is provided in the form of feedback in GPQR, performing phase auto-adjustment of its frequency. The difference in the frequencies of the reference and received signals is proportional to the rate of change of the pseudorange $\dot{\rho}$. At the same time, it should be noted that the PML has astatism of the 3rd order, which allows tracking signals with constant acceleration (the second derivative of the pseudorange). When this circuit captures and follows the phase, it provides a correction signal $\Delta\rho$ in DML, thus increasing the accuracy of pseudorange determination ρ.

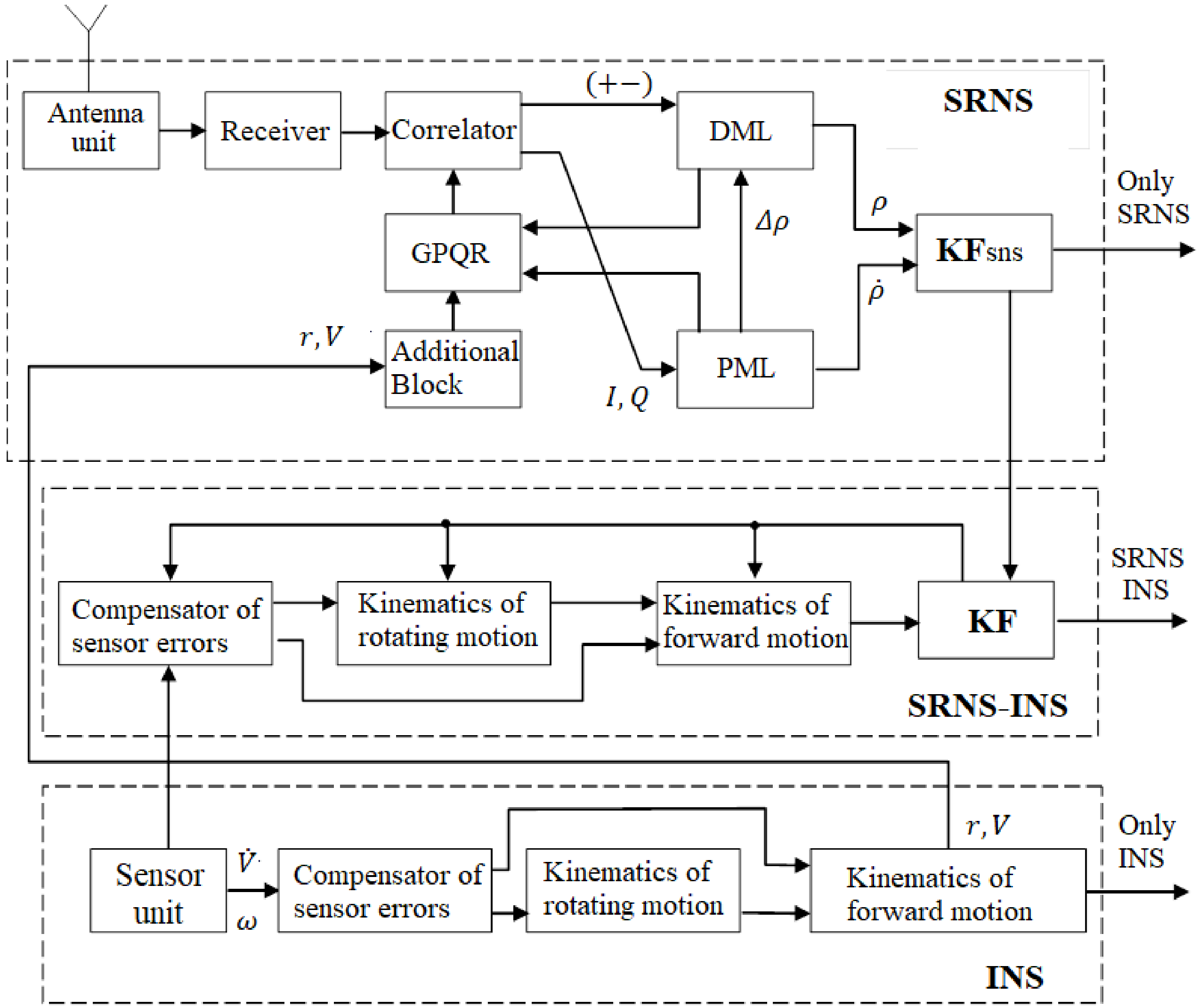

Fig. 1.5 Loosely connected inertial navigation system

Kalman filtering is provided in the satellite system calculator. The Kalman filter of the satellite navigation system (KFsns) is used both for filtering signals of the pseudorange and its rate of change, and for estimating the coordinates and speed of the aircraft (thanks to the interpolation procedure), as well as the shift of the receiver clock relative to the satellite clock, and the speed of the shift of these clocks.

The operation of the satellite system is adjusted with the help of INS at the stage of "cold" and "hot" starts. INS signals are estimated by position (*r*) and speed *(V)* are used by the additional block (AB) of the reception indicator, which automatically adjusts the GPQR of the correlator to reduce the delay search time and the frequencies of the signals generated by the correlator in case of loss of communication with the satellite. Using INS signals, you can start this search with values of delays and frequencies close to the ones you are looking for, which speeds up the “capture” of the corresponding satellite constellations.

In the INS block in fig. 1.5 shows the structure of the platformless inertial system. The sensor unit outputs angular vectors (ω) and linear ($\dot{V}$) coordinates. Compensation of sensor errors according to the types of these errors is performed in a block named "sensor error compensator". It is assumed that the relevant parameters of these sensor models are predetermined or can be calibrated on the bench. In the "Kinematics of rotary motion" block, the kinematic equations of angular motion are integrated based on information from angular velocity sensors. The UAV angular position and angular velocity vectors together with the corrected accelerometer data are used in the block for integrating the kinematic equations of translational motion. At the output of this unit, signals of the location and speed of the UAV appear in the selected navigation system.

In the middle part of Fig. 1.5, the SRNS−INS device is shown, which copies the PINS algorithm and performs complexing of INS and SRNS. The estimation of the parameters characterizing the phase coordinates of the UAV movement is realized in flight based on the results of extended Kalman filtering of the INS and SRNS signals in the KF unit. As a result of the evaluation, the PINS algorithms are corrected by integrating the kinematic equations of rotational and translational movements with Kalman filter correction. Correction of the INS itself in weakly coupled systems is not expected, but calibration and installation of the INS in flight or refinement of the previous ground calibration and installation is possible. This operation, as a rule, is carried out in manned aircraft.

The increased level of autonomy of the INS (it is assumed that the INS subsystem can work autonomously on the order of 1 hour) requires high accuracy of inertial sensors (angular velocity sensors and accelerometers) and the use of rather complex algorithms for integrating the equations of rotational and translational movements. Therefore, such systems are quite expensive and complex. In addition to the high accuracy of INSs, these systems have an important property of redundancy, as they offer solutions to the navigation problem using various methods, which increases controllability and fault tolerance. It is advisable to use such systems on medium- and long-haul civil aviation aircraft, but for UAVs they are too expensive, which makes their use unprofitable.

In rigidly connected systems, the degree of autonomy of the INS is much lower than in loosely connected systems: autonomous operation is allowed for a period of time from several seconds to several tens of seconds. In practice, in these systems, the INS is most often an appendage for the SRNS. The main navigation information is produced in the SRNS, while the INS interpolates the values of the navigation parameters in the period between two adjacent clocks of information from the SRNS, and also provides navigation information to the flight control system in the event of a short-term loss of signals from satellites.

INS in rigidly connected systems (see Fig. 1.6) provides "raw measurements". The sensor unit outputs vectors of angular and linear coordinates.

Compensation of sensor errors according to the models of these errors is performed in the block of the error compensator from the extended Kalman filter. The integration of the kinematic equations of rotational and translational motion is performed taking into account the corrected coordinates. That is, simultaneous procedures are performed in tightly coupled systems: evaluation (filtering) and correction of INS.

The Kalman filter (KF) [15], unlike the previous case, is faster. This is due to the fact that the connection of the KF unit with the contours of the SRNS-navigation receiver is much tighter than in the previous case.

The subsystem of integration of inertial and satellite systems is implemented in the KF unit and estimates the position and speed of the UAV (along with some sensor errors and clock offsets), while this data is provided not only to consumers, but also to the delay (DML) and phase (PML) monitoring loop) of SRNS receivers. It is necessary that these data arrive at a high speed so that the time period between measurements in the SRNS subsystem is divided into a large number of subintervals for the purpose of correction of observation contours. This is necessary in order to supply the surveillance loop with information even when the input signal of the receiver is absent or suppressed by interference.

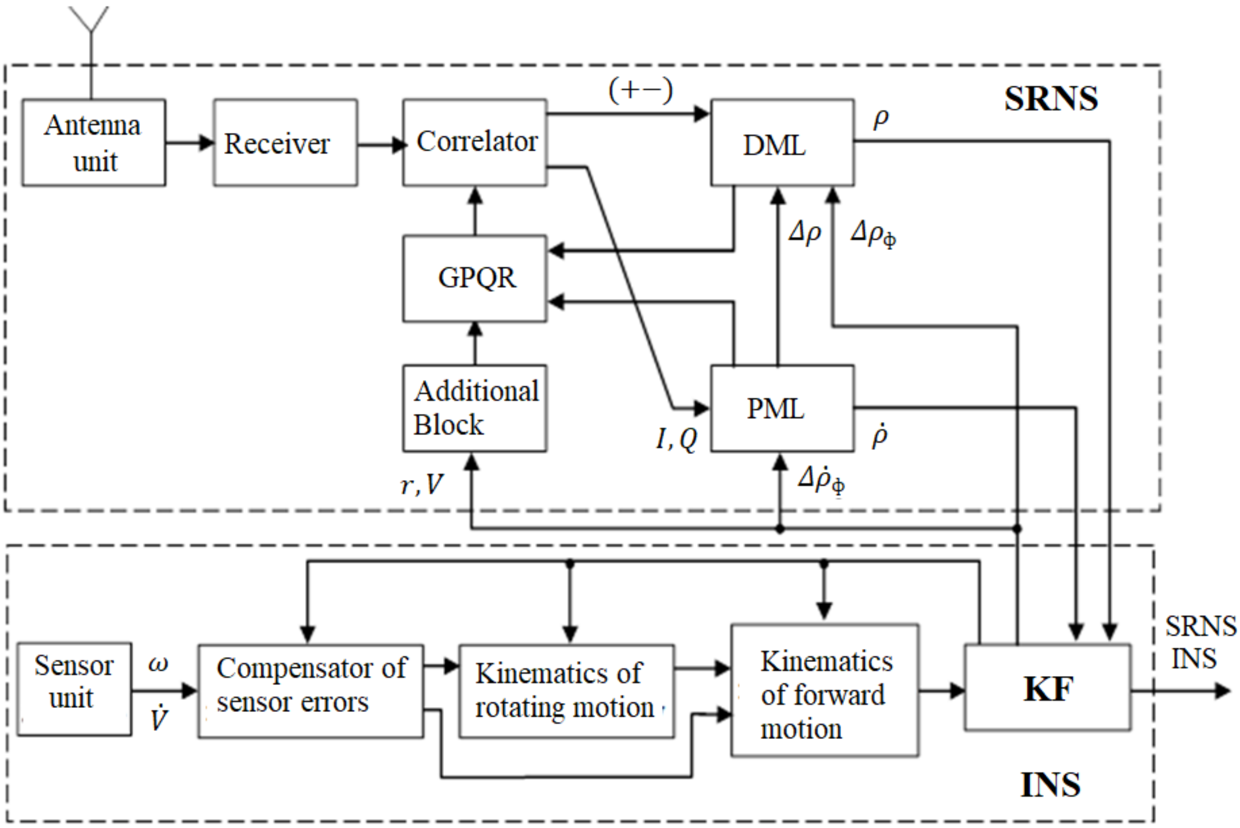

Fig. 1.6 Rigidly connected inertial-satellite system

Rigidly connected systems have higher accuracy using the same inertial sensors compared to loosely connected systems. In these systems, due to additional correction signals from the INS, the bandwidth monitoring loops of SRNS can be significantly reduced. At the same time, the interference resistance of these systems increases and the probability of losing tracked signals decreases. In addition, the application of the Kalman filter, which restores the full state vector, including pseudo range ρ and the speed of its change $\dot{\rho}$, even with incomplete measurements, allows SRNS to work also when the number of visible satellites is less than 4. If the number of these satellites is more than 4, the Kalman filter integrates the information coming from them.

As in loosely connected systems, correction of the SRNS from the corrected INS at the stages of "cold" and "hot" starts is provided here, and the restored pseudorange values ($\Delta\rho_{\Phi}$) and the speed of its change ($\Delta\dot{\rho}_{\Phi}$), entering the loops of monitoring the delay of the DML and the phase of the PML of the SRNS signal, provide an interpolation procedure.

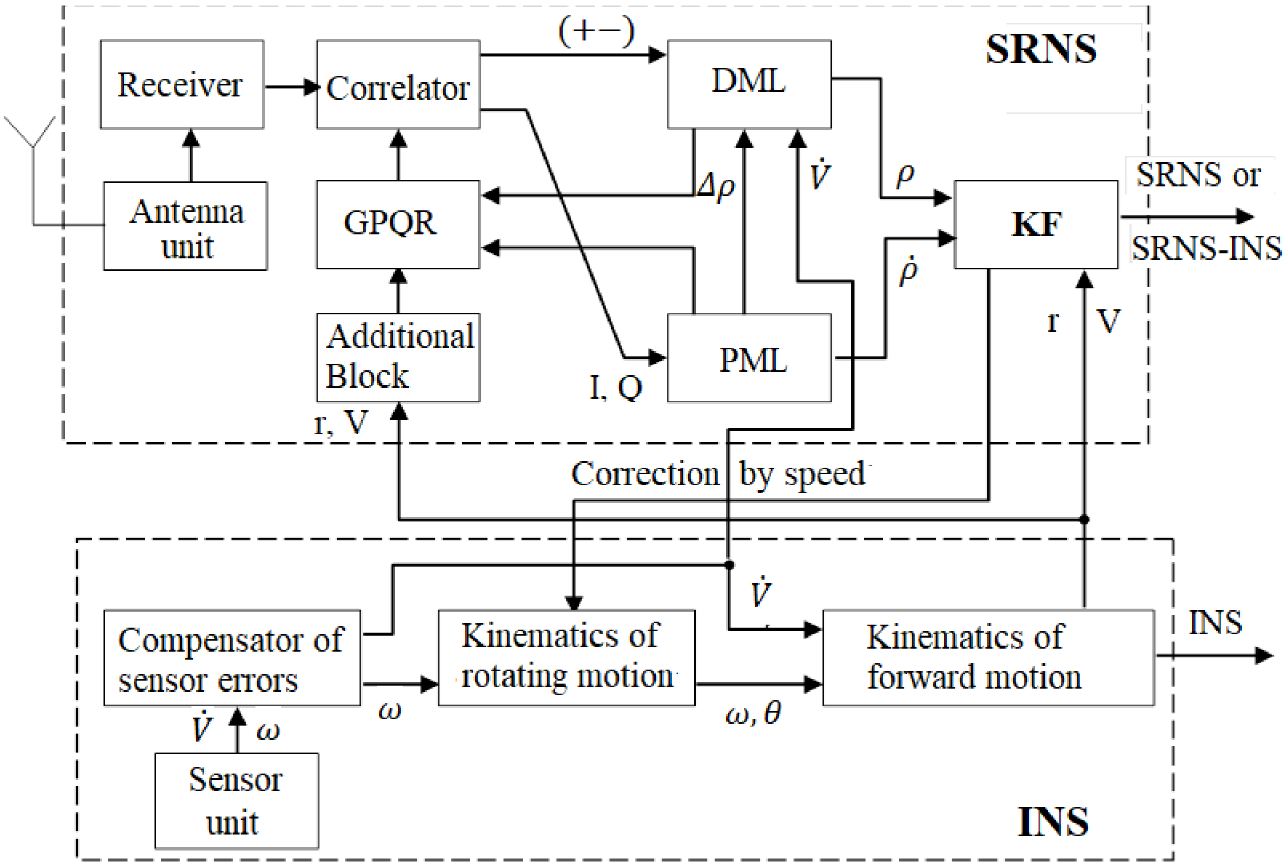

Fig. 1.7 Inertial-satellite system of middle integration

One of the serious disadvantages of systems with tight in comparison with systems with weak integration is the lack of redundancy and a high level of autonomy, which complicates the solution of diagnostic and control tasks.

Therefore, it is advisable to consider another option for integrating SRNS and INS inertial-satellite systems of average integration.

This option (see fig. 1.7) is an intermediate solution between rigid and loosely integration.

The system presented in fig. 1.7 produces two navigation solutions: one of them at the output of the SRNS block, the other at the output of the INS. The blocks presented in the diagram of fig. 1.7, have the same meaning as in the previous schemes. INS provides a solution to the navigation problem in the absence of signals from the SRNS. In addition, a mode of partial correction of the SRNS from the INS, which performs the following functions, is provided. The PML block is a block for monitoring the phase of the carrier frequency, usually more vulnerable to natural or artificial interference. Therefore, if this monitoring unit “lost phase capture” and only the DML unit works - the delay monitoring unit, then the INS replaces the missing signal $\Delta\rho$ on signal $\dot{V}$, thus maintaining the operation of the satellite system without interruption.

ANN in this case, as well as in all others, is also used to extrapolate position signals (r) and speed (V) between two dimensions of SRNS.

Since the entire state vector of the aircraft is restored in the Kalman filter, the angular variables are used to correct the algorithms for integrating the kinematic equations of angular motion, i.e., the speed correction is carried out.

In addition to the considered three variants of the structures of the complex system, there are also other variants built according to the principle of loosely and rigid integration. But at the same time, it should be borne in mind that these options require much more complex and expensive mathematical support, compared to the already considered options for structures.

However, with such an option, the construction of satellite-inertial navigation systems risks the loss of flight information support in the presence of strong radio interference. At the same time, the loss of information about the angular orientation parameters, in particular about the roll and pitch angles, can lead to the loss of the UAV itself. And in the absence of SNS navigation information, only a crude micromechanical PINS is not able to ensure the UAV's exit from the area of effect of radio technical interference and its return to the starting point.

Since ISNS includes a barometric altimeter and a magnetometer, it is logical to introduce an aeromagnetometric system into the INC.

Having in its composition triads of micromechanical inertial sensors, as well as a barometric altimeter and a three-axis magnetometer, AMNS is an auxiliary system of the complex, it prevents the divergence of the vertical and heading channel of the inertial-satellite navigation system, and also implements the inertial-course-air method of calculating coordinates for the period of radio silence of the SNS.

Thus, the proposed deeply integrated UAV navigation complex (Fig. 1.8) is planned to be built on the basis of PINS, GLONASS/GRS satellite navigation system (SNS) receiver and aeromagnetometric navigation system (AMNS), which consists of a three-component magnetometer and a module of aerometric sensors.

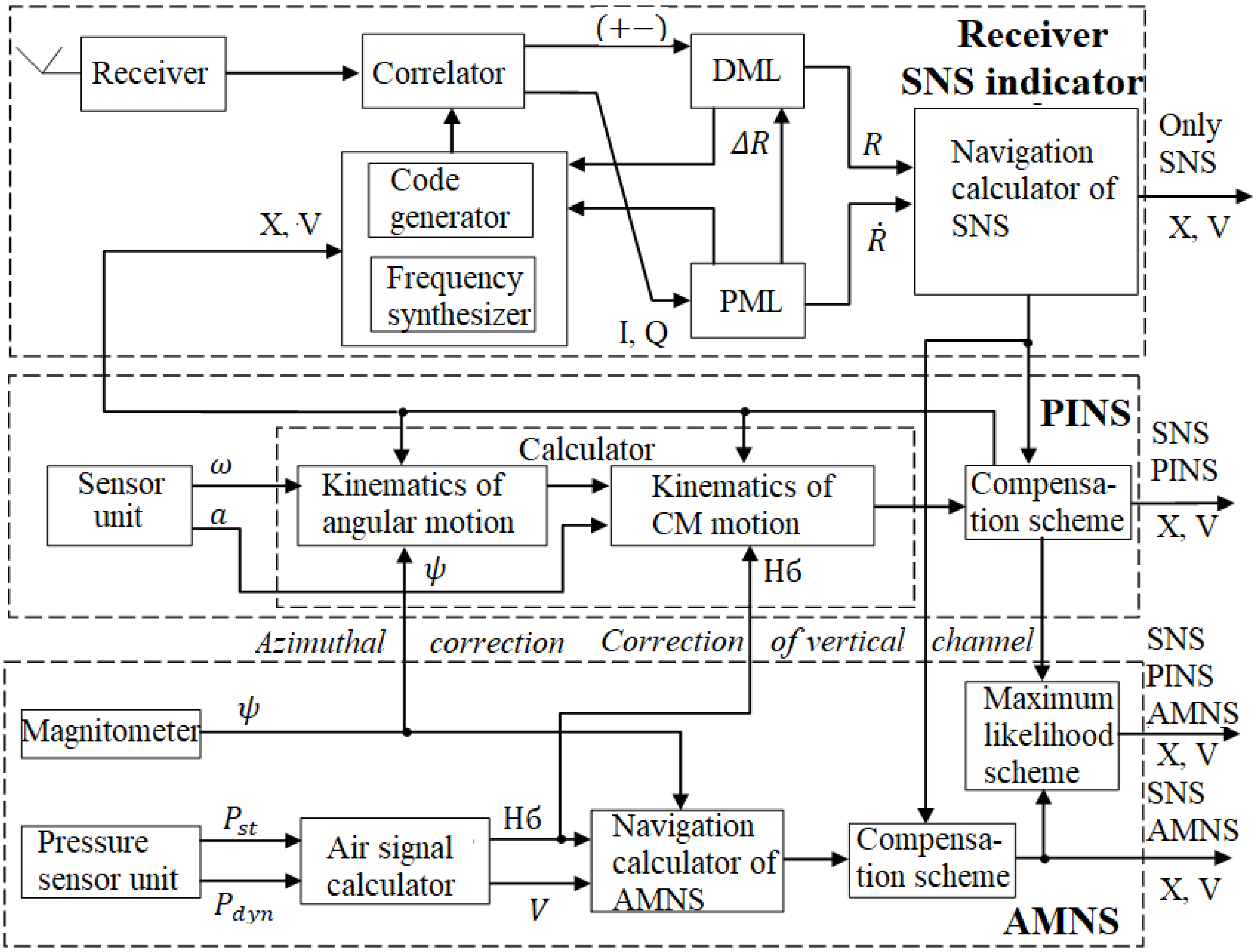

Fig. 1.8 Deeply integrated UAV navigation complex

To solve navigation tasks in the absence of information from the SNS, the UAV navigation complex is usually switched to the course-aerometric path calculation mode.

The problem of the AMNS mode is the difficulty of obtaining information about the angular orientation, in particular about roll and pitch angles. They are trying to solve this problem using alternative methods of non-gyroscopic vertical measurements on board the UAV.

CHAPTER 2. ANALYSIS OF AUTOMATIC CONTROL SYSTEMS OF UNMANNED AERIAL VEHICLE

2.1 Structural diagram of the UAV flight control system

The structural diagram of the UAV control system [16] consists of a flight controller, a drone mechatronics unit, a sensor unit, a navigation system (inertial satellite navigation system), a radio modem, and a ground control station. Also, the satellite navigation system (SNS) interacts with the UAV through the navigation computer.

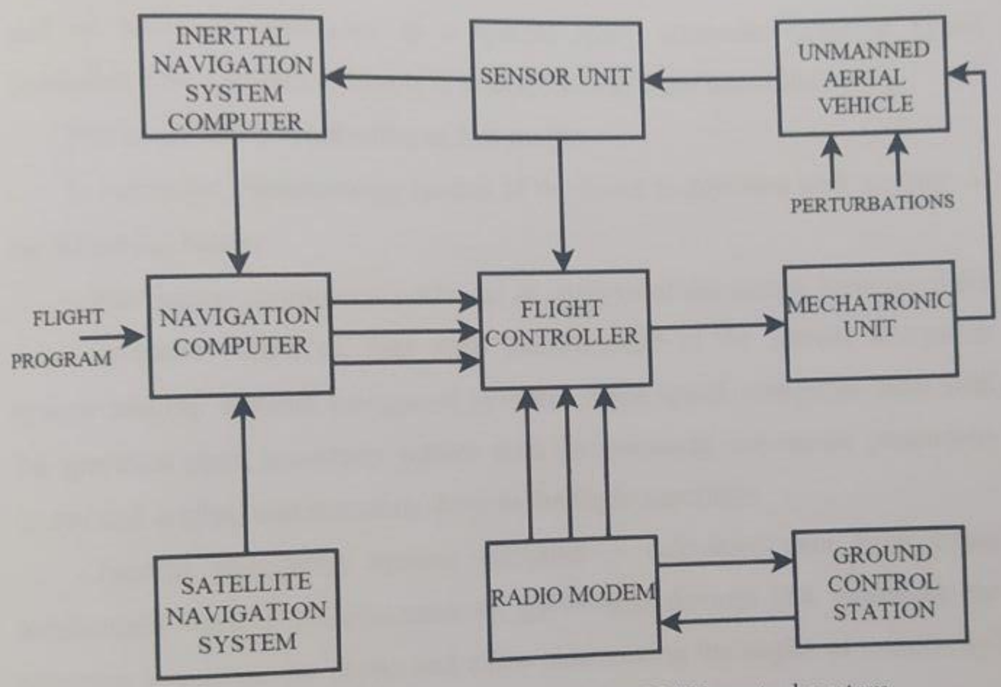

Fig. 2.1 – Structural diagram of the UAV control system

The main element of the control system is the flight controller, the functions of which are to provide regulation and stabilization of the drone's movement in flight and hover mode. The controller compares the received set movement parameters (speed and angles of roll, pitch, yaw) with the current ones coming from the sensor unit and the navigation system. Based on the obtained results, it performs calculations and forms control signals that are transmitted to the mechatronics unit of the drone.

The sensor unit can include a three-axis accelerometer, a three-axis gyroscope, a magnetometer, and a barometric altimeter. The accelerometer measures acceleration, the gyroscope measures angular velocity, and the magnetometer is a magnetic compass that allows the drone to synchronize its position in space. A barometric altimeter is used to stabilize the flight height.

The mechatronics unit of the drone can consist of four brushless motors, each of which is connected to a special speed controller (Electric Speed Controller, ESC), which in turn is connected to the flight controller.

The drone can be controlled in two modes.

1. Autopilot. Autonomous control of the drone is provided with the help of the following blocks:

– Navigation computer – performs an analysis of the current location of the drone in space (based on data from the computer of the inertial navigation system and the satellite navigation system), flight speed, compares them with the specified ones, generates signals with the necessary movement parameters (speed and angles) and transmits them to the flight controller.

– Inertial navigation system computer – calculates data from linear acceleration sensors (accelerometers), gyroscopic devices that reproduce the reference system on the object and allow determining the angles of rotation and inclination of the object, used for its stabilization and motion control.

– The satellite navigation system consists of a GPS module, GLONASS and a 4G modem. GPS and GLONASS modules are used to determine the coordinates of the drone, and the 4G modem is used to transmit data such as flight parameters and video over the Internet.

Autonomous control of the drone is ensured by the implementation of the flight program entered into the navigation computer. In this mode, the navigation computer analyzes the current location of the drone in space (based on data from the inertial satellite navigation system), compares them with the set program values, generates signals with the necessary movement parameters (speed and angles) and transmits them to the flight controller.

2. Manual control. It is provided with the help of a radio modem, which through the antenna from the ground control station (namely, the control panel) receives a signal with the specified movement parameters (speed and angles) and broadcasts them to the flight controller (figure 2.2).

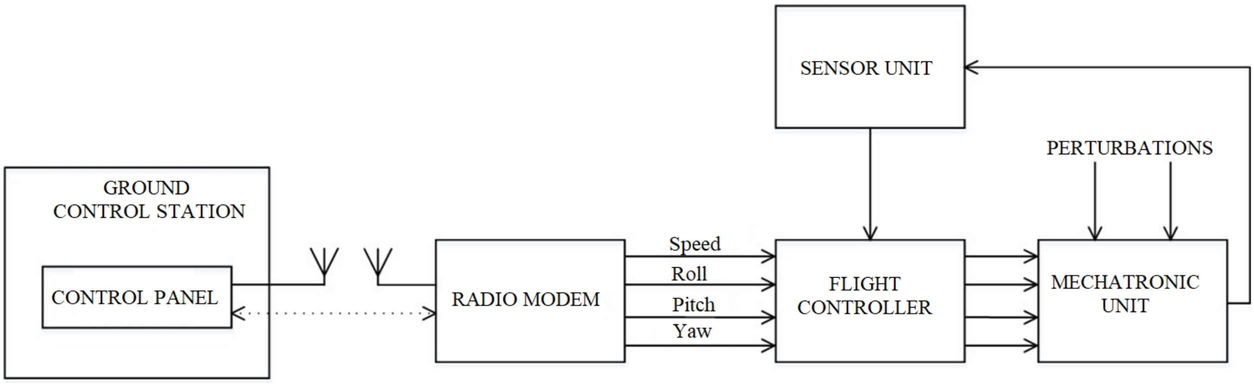

Fig. 2.2 – Scheme of remote-manual control of the UAV

2.2 UAV lateral movement control contours when flying along a route

The methods of controlling the aircraft while flying along the route [17] depend on which navigation parameters are measured and calculated on board the aircraft. There are course, track and route methods of controlling the lateral movement of the aircraft when flying along the route.

2.2.1 Course method of flight control by route

With the course method of flight control along the route, the desired track is not fixed, but only the final navigation point to which the aircraft must be taken is set. It is to this point that the longitudinal axis of the aircraft is directed (Fig. 2.3) and control is carried out according to the difference between the azimuth A_{HT} navigation point (HT) (given in a certain coordinate system in the direction to this point, i.e. a desired course $\psi з = A_{HT}$) and the current aircraft heading ψ, namely by deviation $\Delta\psi = \psi - \psi з$.

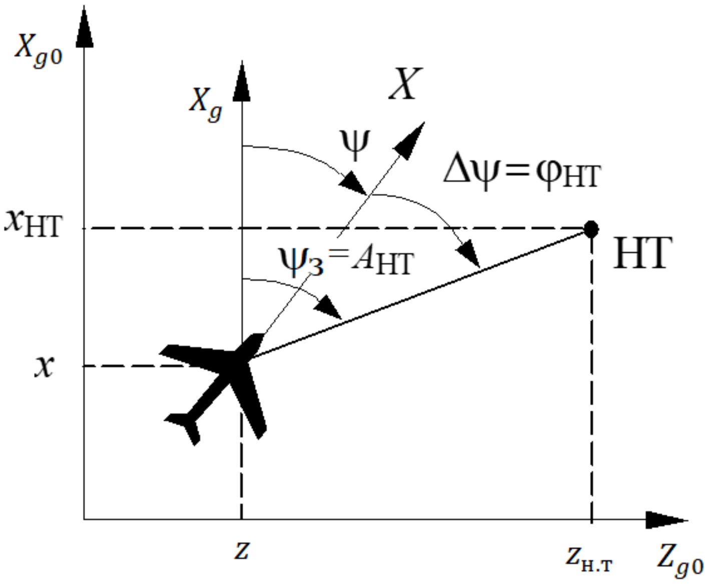

Fig. 2.3 – Aircraft with the course method of flight control

The course method of flight control along the route can be implemented on board the aircraft without too much difficulty, since the control signal (deviation from the direction to the navigation point) is quite simply measured by navigation sensors and can be directly used to control the aircraft. But the uncertainty of the direction of the trajectory and the time of exit to the given point of the route in the presence of a side wind becomes the main disadvantage of this method, that is why it is used as a backup method of flight control along the route.

2.2.2 Track method of flight control by route

The track method of flight control by route [18] is an improved variant of the course method. When implementing the track method, not the longitudinal axis of the aircraft is directed to the given navigation point, but the vector of the route speed $\vec{V}_ш$ (fig. 2.4), that is, control is implemented based on information about the deviation of the current path angle from the given one $\Delta\Psi = \Psi - \Psi з$.

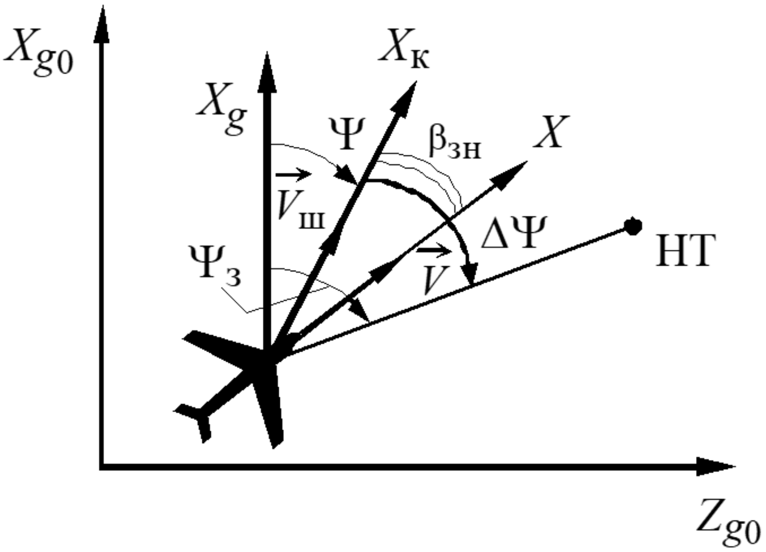

Fig. 2.4 – Aircraft with the track method of flight control

The set track angle is calculated like the set heading, and the drift angle is taken into account when measuring the current track angle:

$$\Psi = \psi - \beta_{зн}$$

Here it is taken into account that in the absence of drifting β the longitudinal axis of the aircraft coincides with the airspeed vector $\vec{V}$, which differs from the direction of the path velocity vector $\vec{V}_ш$ on the drift angle $\beta_{зн}$.

The exit to the next point of the route when implementing this method is carried out in a straight line (the line of the shortest path) even in the presence of a side wind. However, if as a result of active disturbances, the aircraft deviated from the desired track, it no longer returns to it. That is why, when implementing the track flight control method, it remains necessary to periodically correct the given track angle, calculating it depending on the current location of the aircraft, that is, to periodically form a new desired track as the line of the shortest distance to the given navigation point.

The difficulty of implementing the track method of flight control should be attributed to the lack of direct track angle measurements on board the aircraft, and the formation of the track angle based on information about the angle of descent faces certain difficulties associated with the limitation of the operating conditions of the Doppler angle of descent meter, for example, over the water surface.

However, on modern aircraft, the track method is widely used in the automatic control of a route flight, especially when selecting the coordinates of the next turning point or another route navigation point.

On modern aircraft, automatic control of lateral movement is carried out through the channel of the ailerons according to the so-called cross scheme. The rudder is used to damp the oscillations of the aircraft about the normal axis and to compensate for slip. When implementing automatic flight by route, course or track method, unlike course stabilization modes, the set value of the roll angle is limited.

When implementing automatic flight by route, course or track method, control is implemented, as in the yaw angle stabilization modes, through the roll contour using servos with rigid or isodromic feedback.

Unlike the course stabilization modes, the set value of the roll angle is limited. Limit values of the specified bank angle depend on the type of aircraft. For heavy aircraft, they reach 30°, and for maneuverable class I and II aircraft in route flight modes not associated with vigorous maneuvering, the maximum values of the specified roll angle do not exceed 45°. The limitations are due to the fact that with significant changes in the direction of the route, the value of the desired roll angle, which is calculated according to the angle of turn to the new desired track course, may even exceed 90°. The control laws in circuits with isodromic feedback in the servo drive have the form:

$$\frac{T_i p}{T_i p+1}\delta_e = K_\gamma(\gamma-\gamma_з) + K_{\omega_x}\omega_x,$$

where when implementing the course method $\gamma_з = F_{\lim}\frac{K_\psi}{K_\gamma}(\psi-\psi_з)$;

when implementing the track method $\gamma_з = F_{\lim}\frac{K_\Psi}{K_\gamma}(\Psi-\Psi_з)$.

Here $\frac{T_i \mathrm{p}}{T_i \mathrm{p}+1}$ – an isodromic link in the feedback loop of the servo drive, which, while preserving the integrating properties of the steering unit, provides increased control accuracy; δ_{e} – deflection of ailerons; $K_\gamma, K_\psi, K_\Psi, K_{\omega_x}$ – gear ratios; $(\gamma - \gamma_з)$ – deviation of the current roll angle from the set one; $K_{\omega_x}\omega_x$ – the component of the angular rate of roll, which provides damping of the angular oscillations of the aircraft; F_{lim} – the function that forms the limit values of the given roll angle (the function of limiting the given roll angle).

When implementing control through the roll contour with rigid feedback in the servo drive to increase accuracy in the laws of formation $\gamma_з$ But with significant changes in the direction of the route, the integral component at the stage of turning to a new desired track course increases all the time, therefore, after the aircraft enters a new desired track course, this component will force the aircraft to continue turning until the reverse sign deviation signal nullifies this component. The aircraft will again start to return to the desired track course and the whole process will be repeated, there are significant adjustments when processing the given course. That is why the integral component should be connected to the control law only at the stabilization stage, for example, according to the control law:

$$\delta_e = K_\gamma(\gamma - \gamma_з) + K_{\omega_x}\omega_x \tag{2.1}$$

when implementing the course method $\gamma_з = \frac{F_{lim}}{K_\gamma}\left(K_\psi + \frac{K_{\tilde{\psi}}}{P}\right)(\psi - \psi_з)$,

where $K_{\tilde{\psi}} = \begin{cases} 0 & \text{at} \quad (\psi - \psi_з) > \Delta\psi * \\ K_{\tilde{\psi}} & \text{at} \quad (\psi - \psi_з) \le \Delta\psi * \end{cases}$.

Here $\Delta\psi^*$ – certain deviation value $(\psi - \psi_з)$, in which there is a change in the structure of the control law. When implementing the route method of flight control by route instead of a signal (ψ – ψз) use information about the deviation of the current path angle from the given one.

2.2.3 Route method of flight control by route

The route method of flight control allows you to keep the aircraft on a given trajectory, eliminating deviations Δz of the center of mass of the aircraft from the line of the given path (fig. 2.5). This method requires information about the parameters of the deviation from the desired track: the amount of lateral deviation Δ*z*, rate of change of lateral deviation $\dot{z}$, range *Д* to the next turning point.

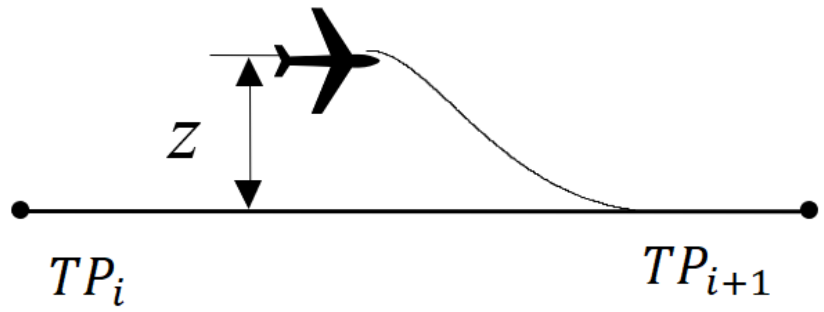

Fig. 2.5 – Aircraft with the route method of flight control

The route method of flight control is widely used when flying along programmed routes, which are stored in the memory of the on-board digital calculator (BDC) of the navigation complex, which includes an inertial navigation system.

When implementing automatic flight along a route, the route method uses the laws of controlling the lateral movement of the center of mass. Control is implemented through the roll circuit using servo drives with rigid or isodromic feedback:

$$\delta_{\text{e}} = K_\gamma(\gamma - \gamma_з) + K_{\omega_x}\omega_x; \quad \frac{T_{ip}}{T_{ip}+1}\delta_e = K_\gamma(\gamma - \gamma_з) + K_{\omega_x}\omega_x.$$

And $\gamma_з$ can be formed according to two typical laws:

$$\gamma_3 = -\frac{F_{lim}}{K_\gamma}(K_z + K_{\dot{z}}p) \cdot \Delta z \quad (2.2)$$

$$\gamma_3 = -\frac{F_{lim}}{K_\gamma}\left[K_z \Delta z - K_\psi(\psi - \psi_{dt})\right] \quad (2.3)$$

here F_{lim} – the function of limiting the given roll angle; Δz – lateral deviation of the center of mass of the aircraft from the desired track; $\psi - \psi_{dt}$– deviation of the current course of aircraft from the course of desired track.

Derivative $\dot{z}$ in the law of formation γ_3 ensures the structural stability of the control circuit. The second version of the control law provides for course control. Presence in the signal control law $\psi - \psi_{dt}$ indicates that the control is carried out through the yaw loop in contrast to the previous control law. Analysis of the static characteristics of such contours shows that under the action of a side wind, the control law of the type (2.2) does not ensure error-free stabilization of the center of mass of the aircraft on the given path line. That is why it is more appropriate instead of a signal $\psi - \psi_{dt}$ form a deviation signal from the path angle of the given path line $\psi - \psi_{dt}$, that is, take into account the angle of drift (side wind). When considering the contours of the automatic control of the lateral movement of the center of mass, other ways of improving the accuracy characteristics were also analyzed.

The flight along the route is classified as flight stages, in which the requirements for the accuracy characteristics of maintaining the aircraft on the desired track are slightly reduced, and this allows the use of control laws without the introduction of additional integral components that reduce the stability of the control circuits. In addition, the measurement errors of the lateral coordinate of the existing inertial navigation systems are 200…500 m per hour of flight and are completely included in the stabilization error even with an astatic control law. However, if measures to improve accuracy characteristics are already provided for other modes of operation of the ACS (for example, a servo drive with isodromic feedback is used), then it is impractical to change the structure of the control channel (replace isodromic feedback with rigid feedback).

2.2.4 Foundation of the methods of flight control along the UAV route at the stage of exiting the active interference zone

At the stage of leaving the zone of active radio interference [19, 20], after the loss of SNS signals, the navigation complex switches to an autonomous mode of operation, using the extrapolated values of the evolution of its errors to maintain acceptable accuracy. With prolonged radio silence, the "return mode" is activated.

In the mode of leaving the zone of action of active interference, the course method of flight along the route must be implemented. At the same time, according to information about the current coordinates of the last location of the UAV x, z (geographic coordinates φ, λ, listed in a rectangular coordinate system) and about the coordinates of the starting point $x_{s.p}, z_{s.p}$ the given rate is calculated (fig. 2.6).

$$\psi_з = \mathrm{arctg}\left[(z_{\mathrm{s.p}} - z) \cdot (x_{\mathrm{s.p}} - x)^{-1}\right] \qquad (2.4)$$

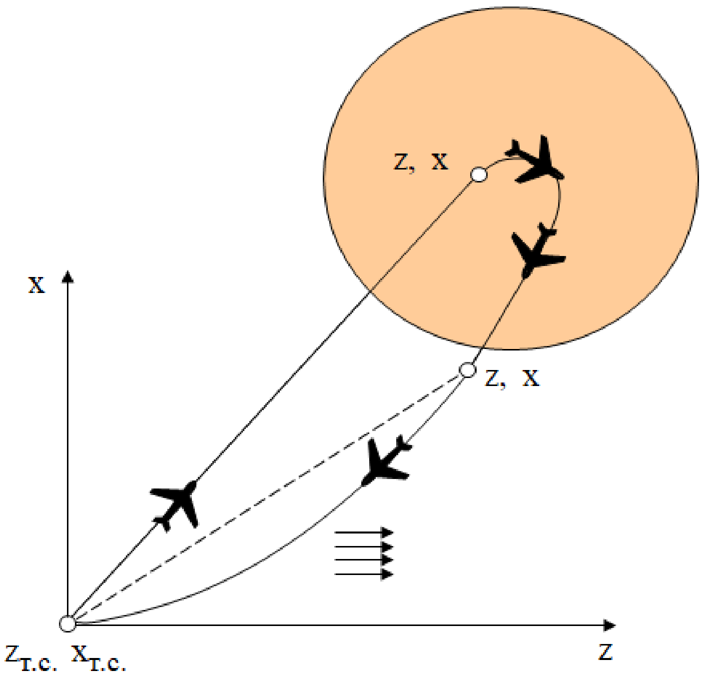

Fig. 2.6 Scheme of returning the UAV from the interference zone to the starting point of the flight

In the aileron control channel δ_e the law of control in the form is implemented:

$$\delta_e = K_\gamma \gamma + F_{lim} K_\psi (\psi - \psi_з) + K_{\omega_x} \omega_x \tag{2.5}$$

where F_{lim} – the function of limiting the given angle of roll, $K_\gamma, K_\psi, K_{\omega_x}$ – gear ratios on roll γ, course ψ, angular velocity ω_x. By implementing this control law, the UAV begins to perform a U-turn to enter the reverse course. In this case, the set value of the course is continuously recalculated, according to the changing values of the current coordinates of the UAV. When the current course coincides with the set course, the mode of its stabilization is activated. Next, the UAV flies to the starting point over the shortest distance, implementing the heading method of flight along the route.

After exiting the zone of action of active interferences, the operation of the SRNS is resumed, then further flight of the UAV to the turning point can be carried out by the route method, quickly forming the given line, or continuing the flight after the route by the course method, periodically correcting the given course according to the formula (2.4), using its own specific position.

In the longitudinal channel, when leaving the zone of active interference, the UAV autopilot operates in the barometric altitude stabilization mode.

For astatic stabilization of the given flight height $H_з$ channels with isodromic feedback are used $\left(W_{зз}(p) = \frac{T_i p}{T_i p+1}\right)$ or add integrating links $\left(W_{\Delta H}(p) = K_H + \frac{K_{\tilde{H}}}{p}\right)$ in the law of formation of a given pitch angle in autopilots with rigid feedback.

Note that the given value of the pitch angle $\vartheta_з$, which is formed by the trajectory contour, is compared with the deviation of the pitch angle from the balancing value (from the pitch angle of horizontal flight $\vartheta_{\text{h.p}}$).

The simplest typical altitude control law implemented in a hard-feedback pitch autopilot looks like:

$$\delta_в = K_\vartheta(\vartheta^* - \vartheta_з) + W_{\omega_z}(p)\omega_z \tag{2.6}$$

where $\vartheta^* = \vartheta - \vartheta_{\text{h.p}}$; $\vartheta_з = -\frac{K_H}{K_\vartheta}(H - H_з)$; $W_{\omega_z}(p)$ – correction filter in the signal circuit of the angular velocity sensor (band filter or isodromic link); K_H, K_ϑ – transfer numbers of the control law.

Transforming the control law (2.6), we write

$$\delta_в = K_\vartheta\left(\vartheta - \vartheta_{\text{h.p}}\right) + K_H(H - H_з) + W_{\omega z}(p)\omega_z \tag{2.7}$$

Analyzing the variants of the control laws considered above, we note that they are built on the basis of the UAV angular motion control contours. In particular, these are the roll and pitch control contours. But, if the information about the angles of roll and pitch is obtained by estimating the state vector, then malfunctions of the SNS will almost instantly lead to the distortion of this information. Distortion of aerobatic information leads to unacceptable evolution of the UAV and, as a result, to its loss.

Therefore, the work proposes to develop algorithms for automatic UAV control circuits at the stage of exit from the zone of active radio interference, which are based on sensors for direct autonomous measurement of aerobatic parameters only.

CHAPTER 3. DEVELOPMENT OF ALTITUDE CONTROL CIRCUITS BASED ON THE NORMAL OVERLOAD CONTROL CIRCUIT

3.1 Analysis of static and dynamic characteristics of flight height control processes using the normal overload circuit

When flying in the area of active radio interference, it is proposed to change the structure of the control circuit as an internal circuit in the pitch rudder channel, using instead of the pitch circuit, the normal overload control circuit. Thus, it becomes possible to exclude the influence of malfunctions in the algorithms of the inertial-satellite navigation system when evaluating the pitch angle on the safety of the UAV flight. The control law in this case is transformed into a species:

$$\delta_{\text{в}} = \frac{K_{n_y}}{\mathrm{T}_{n_y}p + 1}\left(\Delta n_y - \Delta n_{y_3}\right) + K_{\omega_z}\omega_z \tag{3.1}$$

Where $\Delta n_{y_з} = -\frac{1}{K_{n_y}}\left(K_H \Delta H + K_{V_y} V_y\right)$; ΔH – deviation from the set flight height; K_{n_y}, K_{V_y} – transfer numbers of the control law; $V_y = pH$ – vertical speed, which ensures the structural stability of the control circuit. Information about the current overload $(\Delta n_y = n_{y-1})$ where $n_y = \frac{a_y}{g}$, can be obtained from the PINS vertical accelerometer, taking into account that (a_y – vertical acceleration as measured by an accelerometer, g – the acceleration of gravity, which is equal to $9.81\ m/c^2$.

Accelerations measured by an accelerometer have a noise and systematic error component. The noise component of measurements, is filtered by an aperiodic filter $\frac{1}{\mathrm{T}_{n_y}p+1}$, and the systematic error component of the accelerometer is quasi-stationary, in contrast to the time-growing errors of pitch angle formation.

The structure of such a control loop is shown in Fig. 3.1.

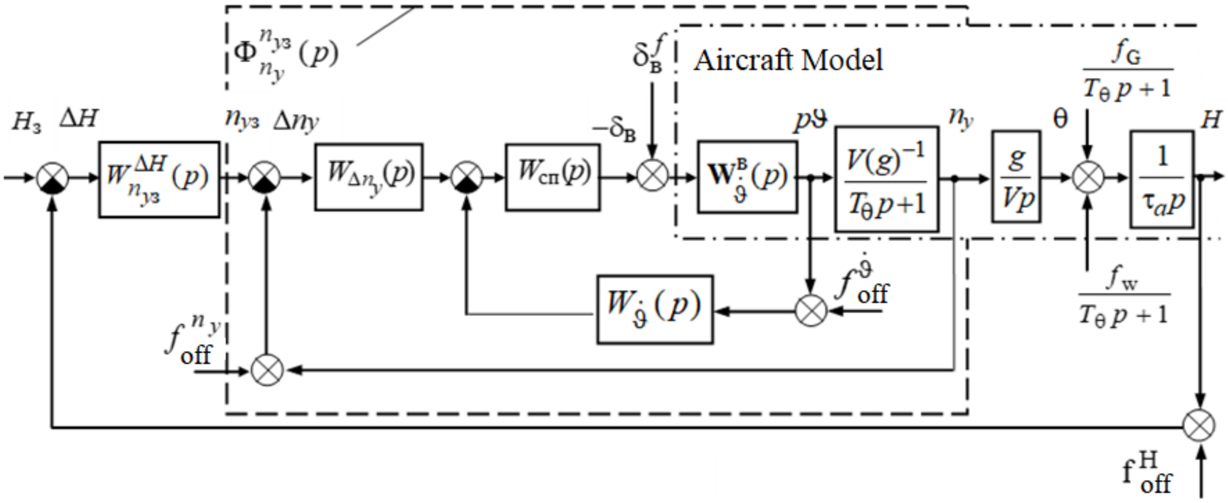

Fig. 3.1 Structure scheme of the normal overload control circuit

From the analysis of the structural diagram, it follows that the introduction of the derivative of the deviation from the given height into the control law of the signal is a necessarily condition. Otherwise, the circuit is structurally unstable.

Internal loop transfer function $\Phi_{n_y}^{n_{y з}}(\mathrm{p})$ at $W_{\dot{\vartheta}}(\mathrm{p}) = K_{\dot{\vartheta}}$, $W_{\Delta n_y}(p) = K_{n_y}, W_{сп}(\mathrm{p}) = 1$, will look like:

$$\Phi_{n_y}^{n_{y з}}(\mathrm{p}) = \frac{W_{n_y}(\mathrm{p})}{1 + W_{n_y}(\mathrm{p})} = \frac{K_{n_y}^{n_{y з}}}{\left(\frac{\mathrm{p}^2}{\omega_{n_y}^2} + 2\frac{\xi_{n_y}}{\omega_{n_y}}\mathrm{p} + 1\right)} \tag{3.2}$$

Where $W_{n_y}(\mathrm{p}) = \frac{V\, K_{n_y} W_{\vartheta_Д}^{В}(\mathrm{p})}{g(T_\theta\,\mathrm{p}+1)}$; $\omega_{n_y} = \omega_\alpha \sqrt{1 + K_{\dot{\vartheta}}\, K_{\dot{\vartheta}}^{В} + K_{n_y} \frac{V}{g} K_{\dot{\vartheta}}^{В}}$;

$$\xi_{n_y} = \frac{2\xi_\alpha \omega_\alpha + K_{\dot{\vartheta}}\, K_{\dot{\vartheta}}^{В}\, \omega_\alpha^2\, T_\theta}{2\omega_\alpha \sqrt{1 + K_{\dot{\vartheta}}\, K_{\dot{\vartheta}}^{В} + K_{n_y}\frac{V}{g} K_{\dot{\vartheta}}^{В}}}; \quad K_{n_y}^{n_{y з}} = \left[\frac{g\left(1 + K_{\dot{\vartheta}}\, K_{\dot{\vartheta}}^{В}\right)}{V\, K_{n_y}\, K_{\dot{\vartheta}}^{В}} + 1\right]^{-1}.$$

The transfer function of the altitude circuit control with considering (3.2)

$$W_{n_{y_з}}^{\Delta H}(\mathrm{p}) = \frac{K_H}{K_{n_y}}\left(\frac{K_{\dot{H}}}{K_H}\mathrm{p} + 1\right)$$

will be written in the form

$$W_H(\mathrm{p}) = \frac{K_{\text{пс}}\left(\frac{K_{\dot{H}}}{K_H}\mathrm{p} + 1\right)}{\mathrm{p}^2\left(\frac{\mathrm{p}^2}{\omega_{n_y}^2} + 2\frac{\xi_{n_y}}{\omega_{n_y}}\mathrm{p} + 1\right)} \qquad (3.3)$$

Where $K_{\text{пс}} = \frac{g}{V\,\tau_a}\frac{K_H K_{n_y}^{n_{y_з}}}{K_{ny}}$.

The analysis of the Bode magnitude diagram corresponding to (3.3) at different values of the transfer numbers (Fig. 3.2) shows that an increase K_{n_y} causes a damping effect on pitch fluctuations with frequencies $f \approx \omega_{n_y}$, but increases low-frequency oscillations with $f \approx \frac{K_H}{K_{\dot{H}}}$. Increasing $K_{\dot{H}}$ on the contrary, it reduces low-frequency oscillations ($f \approx \frac{K_H}{K_{\dot{H}}}$), but increases oscillations with frequencies $f \approx \omega_{n_y}$. When increasing K_H the link with a slope of -20db/dec decreases, stability deteriorates, oscillations occur in the circuit.

The structural analysis of the control circuit (see Fig. 3.1) shows that the circuit provides first-order astatism even for an astatic auxiliary power unit (APU) when the aircraft falls into vertical air flows (disturbance f_w). In relation to instant disturbances in the circuit, a static error will occur.

The constant component of the vertical acceleration measurement errors $f_{\text{meas}}^{n_y}$, reduced to the input of the internal circuit - normal overload control circuit $\Phi_{n_y}^{n_{y_з}}$, as well as barometric flight altitude error $f_{\text{meas}}^{\text{H}}$ cause, naturally, a constant error in altitude stabilization.

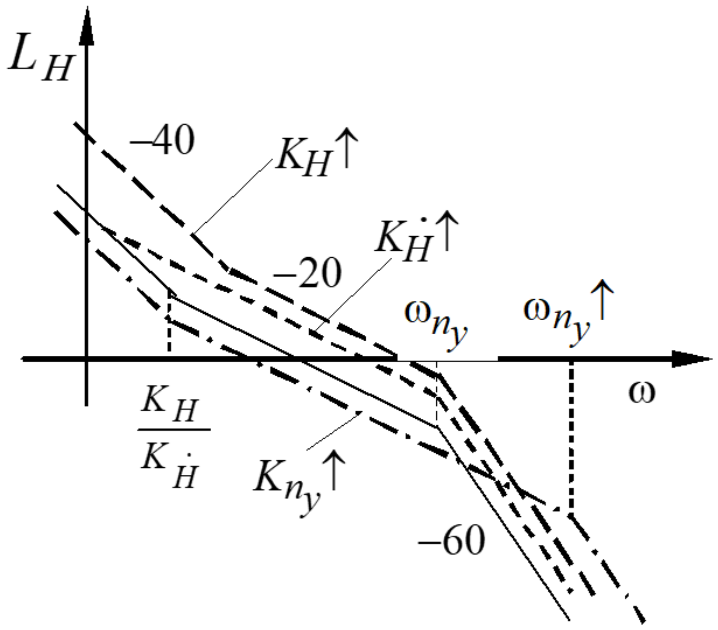

Fig. 3.2 Bode magnitude diagram

It should be noted that in the contour based on the pitch roll, the errors in the formation of the pitch angle that increase with time lead to increasing errors in the stabilization of the flight altitude.

As for the internal contour, there is an astatic APU ($W_{\Delta n_y}(p) = K_{n_y} + \frac{K_{\tilde{n}y}}{p}$) or isodromic feedback channels in a servo ($W_{сп}(p) = \frac{T_i p+1}{T_i p}$), then instant disturbances will be compensated without altitude stabilization errors.

When maneuvering in a vertical plane in such a control loop, it is much easier to implement control actions by forming a given value of the vertical speed $V_{yз}$ as a function of the given flight altitude.

$$\Delta n_{y_з} = -\frac{K_{V_y}}{K_{n_y}}\left[(V_y - F_{lim}^{V_y} V_{yз}(H - H_з)\right]$$

Here $F_{\lim}^{V_y}$– restrictions on the vertical rate of climb and descent.

Similar circuits used on maneuverable aircraft have shown their high efficiency, as they have an increased speed compared to the pitch angle control circuits.

CHAPTER 4. DEVELOPMENT OF FLIGHT CONTROL CIRCUITS FOR LATERAL MOVEMENT

4.1 Research of lateral movement control circuit

Note that in the aileron channel, as well as in the elevator channel, it is necessary to exclude the influence of failures in the operation of the algorithms for estimating the angular orientation parameters on the safety of the UAV flight. An attempt to switch to lateral movement control [21] through the rudder channel, using only magnetometer information in this channel, which is obtained by direct measurement of the UAV magnetic heading, does not give positive results. This is due to the fact that in the aileron channel it will still be necessary to ensure the stabilization of the zero-roll angle, the reliability of which at the flight stage in the zone of active radio interference is questionable. Therefore, instead of the classical control law (2.1) can be rewritten:

$$\delta_e = K_\gamma \gamma + F_{lim} K_\psi (\psi - \psi_з) + K_{\omega_x} \omega_x, \tag{4.1}$$

the paper proposes the following algorithm for the implementation of control actions in the aileron channel:

$$\delta_e = K_{\omega_y}(V)\, \omega_y + F_{lim} K_\psi (\psi - \psi_з) + K_{\omega_x} \omega_x \tag{4.2}$$

here component ω_y replaces the roll signal in the control law, taking into account that during turns $\omega_y \approx \left(\frac{g}{V}\right) \mathrm{tg}\gamma$; $K_{\omega_y}(V)$ – gear ratio for angular velocity ω_y, airspeed corrected V.

Signals ω_y, ω_x are measured by the block of PINS inertial sensors, and the signal of the current magnetic heading comes from the magnetometer, i.e., these signals are direct offline measurement signals.

The investigation of the proposed UAV lateral motion control loops was carried out by mathematical modeling using the Simulink program, which is part of the MATLAB mathematical software package.

During the research, the UAV model was presented as a system of linear differential equations describing the dynamics of the UAV lateral movement in deviations:

$$\begin{gathered}
\dot{\Psi} = a_z^{\beta}\beta + a_z^{\gamma}\gamma + a_z^{\delta_н}\delta_н; \\
\dot{\omega}_x = -a_{m_x}^{\omega_x}\omega_x - a_{m_x}^{\omega_y}\omega_y - a_{m_x}^{\beta}\beta + a_{m_x}^{\delta_н}\delta_н + a_{m_x}^{\delta_е}\delta_э + m_x^f; \\
\dot{\omega}_y = -a_{m_y}^{\omega_x}\omega_x - a_{m_y}^{\omega_y}\omega_y - a_{m_y}^{\beta}\beta + a_{m_y}^{\delta_н}\delta_н + a_{m_y}^{\delta_е}\delta_э + m_y^f; \\
\dot{\psi} = \omega_y \cos\gamma + f_{\omega_z} \sin\gamma; \\
\dot{\gamma} = \omega_x; \\
\beta = \psi - \Psi + \beta_w.
\end{gathered} \tag{4.3}$$

Here, additional notations are used: Ψ – path angle, β – slip angle, $\delta_н$ – rudder deflection; $a_{m_z}^k$, $a_{m_y}^k$, $a_{m_x}^k$, where $k = \beta, \gamma, \omega_x, \omega_y, \delta_н, \delta_э$ – coefficients of the mathematical model, taking into account the aerodynamic characteristics of the UAV.

At the same time, for comparative analysis, two variants of control laws (3) and (4) in the aileron and rudder channel were modeled. In the rudder channel, the classical control law was modeled, which provides damping of the oscillatory component of the yaw motion:

$\delta_н = K_{\omega_y}\omega_y$.

To carrying research, the system of equations for the UAV motion dynamics was supplemented by disturbing influences – $m_x^f, m_y^f, \beta_w, f_{\omega_z}$, imitating moment disturbances along two axes, wind disturbances and changes in the yaw angular velocity with a change in the pitch angular velocity.

Moreover, wind disturbances were modeled both in the form of a constant drift angle and in the form of a turbulent disturbance.

Errors of information sensors of control loops were simulated by deterministic and noise components of the signals of these sensors.

On fig. 4.1 shows the simulation results illustrating changes in the parameters of lateral movement when the UAV performs a 90° turn using control laws (4.2) and (4.3)

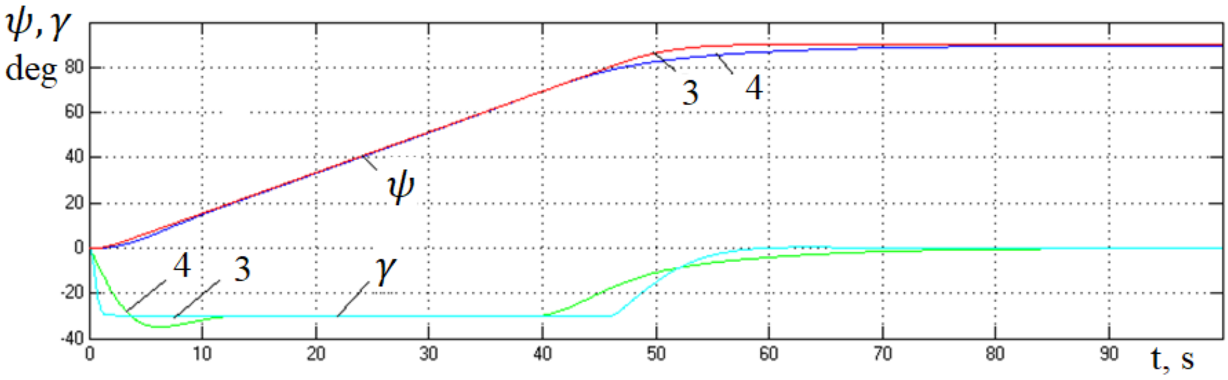

Fig. 4.1 Result of simulation of lateral movement when the UAV performs a 90° turn

An analysis of the simulation results shows that there are no special differences in the processing of control signals by different control loops, only the processes in the control loop (4.3) are somewhat delayed.

To eliminate this shortcoming, additional cross-couplings were introduced into the aileron control law (4.2), taking into account the dynamics of the roll angle change $\gamma \approx \frac{(\omega_y - a_z^\beta \beta - \dot{\beta})}{a_z^\gamma}$, and the rudder channel is set to slip compensation mode. Control laws when taking into account that the lateral overload signal $n_z \equiv \beta$, take the following form:

$$\delta_{\text{e}} = K_{\omega_y}\omega_y + \frac{1}{T_{n_y}p+1}\left(K_{n_z} + p\frac{K_{\dot{n}_z}}{T_f p+1}\right)n_z + F_{orp}\text{K}_{\psi}(\psi - \psi_{\text{з}}) + K_{\omega_x}\omega_x;$$
$$\delta_{\text{н}} = \frac{K_{\omega_y}p}{T_{\omega_y}p+1}\omega_y + K_{n_z}n_z. \quad (4.4)$$

Here is the aperiodic filter $\frac{1}{\text{T}_{n_y}p+1}$ filters out the noise component of the lateral overload measurements, and the filter $\frac{1}{\text{T}_f p+1}$ – additional noise component of this signal resulting from differentiation. Isodromic filter in the rudder channel $\frac{p}{T_{\omega_y}p+1}$ cuts off constant component ω_y, interfering with the turn of the UAV.

Comparative investigations of these control loops and the control loop that implements the control law (4.4) show their complete identity when working out a given course (see Fig. 4.2).

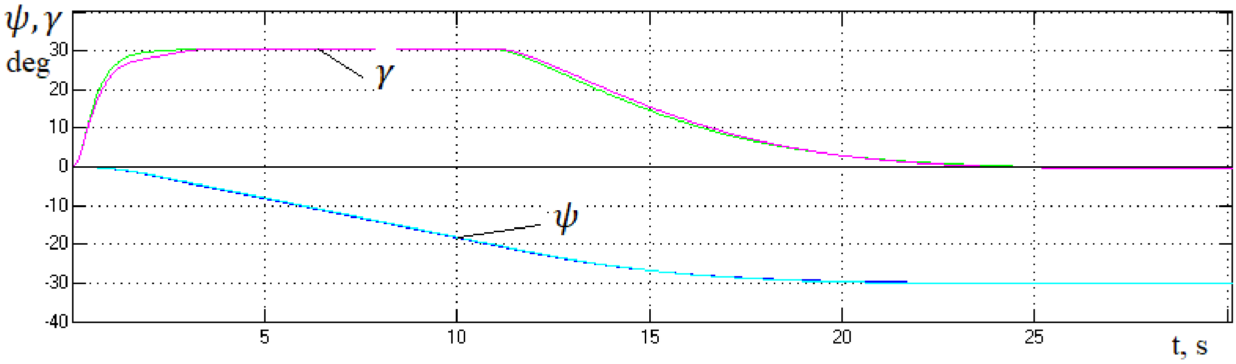

Fig. 4.2 Result of simulation of lateral movement when the UAV performs a 30° turn

We also analyzed the processes of parrying momentary disturbances by control loops using control laws (4.4), (4.2). On fig. 4.3 shows the results of modeling processes, parrying the rolling moment m_x^f. Analysis of the simulation results also show the complete identity of the studied control loops.

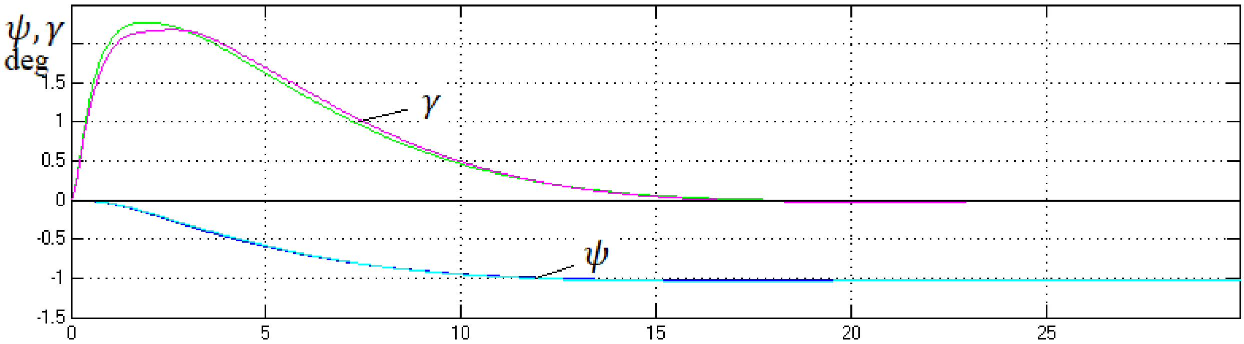

Fig. 4.3 Results of modeling processes, parrying the rolling moment m_x^f

Fig. 4.4 illustrates the transient processes in the control loops (4.4), (4.2) when parrying the turning moment m_y^f.

Here, when working out the disturbing moment m_y^f by control loop (4.4) observes the initial rollback reaction caused by the helical moment. However, in general, the processes of compensating the turning moment are quite satisfactory.

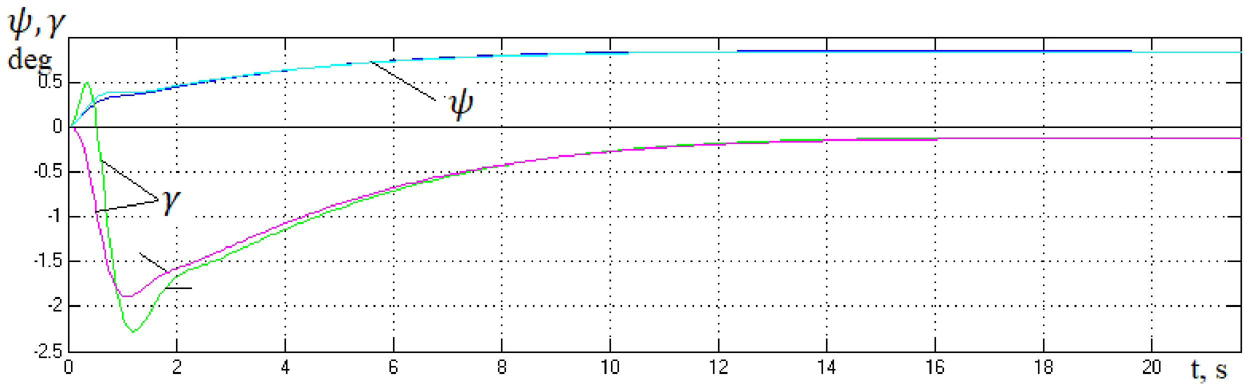

Fig. 4.4 Transient processes in the control loops when parrying the turning moment m_y^f

And finally, the developed control loop was investigated at the stage of UAV flight in a turbulent atmosphere. In this case, the errors of the information sensors of the control loops were simulated. The simulation results are shown in fig. 4.5.

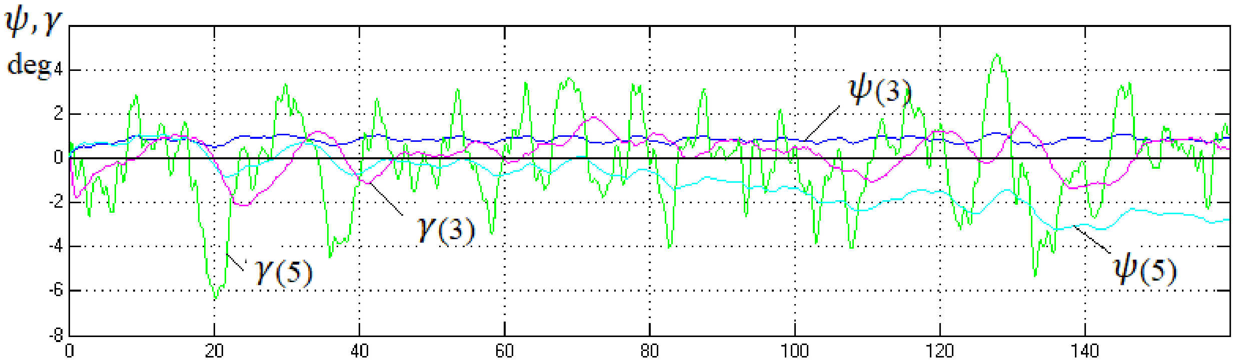

Fig. 4.5 Research of the developed roll control loop at the UAV flight stage in a turbulent atmosphere

An analysis of the simulation results shows that, due to the vigorous parrying of wind disturbances by a roll maneuver, loop (3) provides an increased accuracy of stabilization of the main navigation parameter - deviation from a given flight course. The same cannot be said about the control loop (5), in which the heading stabilization error, which grows with time, eventually leads to a failure of the bank angle stabilization and the UAV enters critical flight modes (see Fig. 4.6).

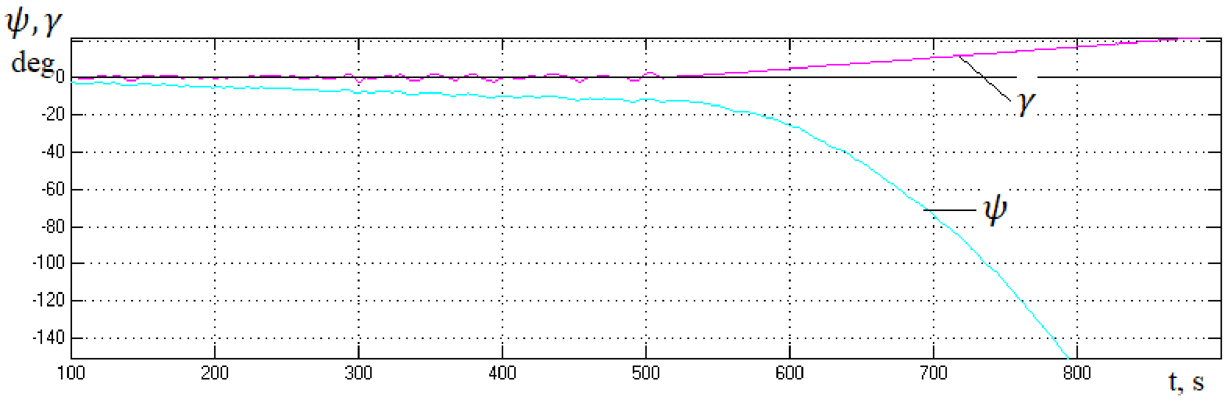

Fig. 4.6 Research of the developed roll control loop at the UAV flight stage in a sharp turn

Note that the reconfiguration of the control loops in no way affects the algorithms for solving PINS navigation problems, in particular, the algorithms for generating the matrix of direction cosines that require information about the parameters of the angular orientation. Moreover, by analyzing the statistical values of the rates of change of the roll and pitch angles, which are the angular parameters of the UAVs not involved in the formation of the UAV flight control laws, on steady-state straight flight sections, it is possible to estimate the errors of the primary information sensors.

CHAPTER 5. DEVELOPMENT AND RESEARCH OF UAV ALTITUDE CONTROL ALGORITHMS

5.1 Development of a mathematical model of the longitudinal movement of the UAV

The basis of the synthesis of any automatic control circuit is the mathematical model of the control object, in our case it is the mathematical model of the UAV, which should be suitable for the synthesis of UAV control circuits when flying along the route, as well as for carrying research on automatic control circuits by means of mathematical modeling of the flight dynamics of UAVs of this type. Linear mathematical models are usually used for such purposes.

Longitudinal movement refers to the movement of the aircraft in the vertical plane without roll and slip when the rudder and roll controls (ailerons) are in a neutral position. At the same time, two translational and one rotational movement occur. Forward movement is carried out along the velocity vector and normal to it, and rotational movement occurs around the transverse axis OZ. Longitudinal movement is characterized by the angle of attack α, by the angle of inclination of the trajectory Θ, pitch angle ϑ, speed V and flight height H, as well as the angle of deviation of the height rudder $\delta_в$ and thrust P of the power plant.

Separation of equations of longitudinal motion from the complete system of equations of spatial motion. System of equations of longitudinal motion of the aircraft.

The closed system of equations that describes the longitudinal motion of the aircraft can be separated from the full system of equations under the conditions that the parameters of the lateral movement, as well as the deflection angles of the control bodies $\delta_e, \delta_н$ are equal to zero.

Then the system of equations describing the isolated longitudinal motion of the aircraft is reduced to the form:

$$m\dot{V} = P\,cos\,a - X_a - mg\,sin\,\Theta\,;$$
$$mV\dot{\Theta} = P\sin a + Y_a - mg\cos\Theta\,;$$
$$I_z\dot{\omega}_z = M_z;$$
$$\dot{\vartheta} = \omega_z;\qquad (5.1)$$
$$a = \vartheta - \Theta;$$
$$\dot{H} = V\,sin\,\Theta,$$

where $mg = G, g$ - free fall acceleration.

Kinematic ratio $\alpha = \vartheta - \Theta$ obtained from the first geometric equation after transforming it using the formula for subtracting arguments of trigonometric functions.

The last equation does not affect the other equations of the system, so the system can be considered without it.

The system of equations (5.1) is non-linear, as it contains products of variables and trigonometric dependencies, as well as expressions for aerodynamic forces and moments as non-linear flight functions.

To obtain a simplified linear model of aircraft motion, additional assumptions must be made and the original equations linearized.

Derivation of linearized equations based on the complete system of equations of isolated longitudinal motion.

To linearize the nonlinear system of equations (5.1), it is necessary to assign undisturbed (programmed) motion. As a rule, the mode of rectilinear horizontal flight with a constant speed is selected for program movement. Undisturbed motion corresponds to the original system of equations under certain initial conditions:

$$
\begin{aligned}
m\dot{V}_0 &= P_0 \cos a - X_{a0} - mg \sin \Theta_0 ;\\
mV_0\dot{\Theta}_0 &= P_0 \sin a_0 + Y_{a0} - mg \cos \Theta_0 ;\\
I_z\dot{\omega}_{z0} &= M_{z0};\\
\dot{\vartheta}_0 &= \omega_{z0};\\
a_0 &= \vartheta_0 - \Theta_0;\\
\dot{H}_0 &= V_0 \sin \Theta_0,
\end{aligned} \tag{5.2}
$$

The parameters of the disturbed motion must be presented as the sum of the parameters of the undisturbed motion and small deviations.

$$
\begin{gathered}
V = V_0 + \Delta V; P = P_0 + \Delta P; X_a = X_{a0} + \Delta X_a;\\
Y_a = Y_{a0} + \Delta Y_a;\ M_z = M_{z0} + \Delta M_z;\ \Theta = \Theta_0 + \Delta\Theta;\\
\vartheta = \vartheta_0 + \Delta\vartheta;\ a = a_0 + \Delta a;\ \delta_{\text{в}} = \delta_{\text{в}0} + \Delta\delta_{\text{в}};\\
\delta_{\text{р}} = \delta_{\text{р}0} + \Delta\delta_{\text{р}};\ H = H_0 + \Delta H.
\end{gathered} \tag{5.3}
$$

Since the derivatives of the parameters of undisturbed motion (from the constant values) are equal to zero, the obvious relations:

$$\dot{V} = \Delta\dot{V};\ \dot{\vartheta} = \Delta\dot{\vartheta};\ \dot{a} = \Delta\dot{a}; \ldots$$

To present the nonlinear dependences of the original system of equations in the form (5.3), we expand these functions into a Taylor series, limiting ourselves only to the linear terms of the expansion. The partial derivatives included in the expressions for the power series are determined at the point corresponding to undisturbed motion. In aerodynamics, it is customary to mark them with a superscript corresponding to the parameter from which the derivative is taken.

Example,

$$\frac{\partial Y_a}{\partial a} = Y_a^a;\ \frac{\partial M_z}{\partial a} = M_z^a$$

Decomposition of nonlinear dependencies into a Taylor series with consideration

$$X_a = X_a(V, H, a); Y_a = Y_a(V, H, a); M_z = M_z(V, H, a, \dot{a}, \omega_z, \delta_{\text{в}}); P = P(V, H, \delta_{\text{р}})$$

Looks like:

$$
\begin{gathered}
Y_a = Y_{a0} + Y_a^V \Delta V + Y_a^H \Delta H + Y_a^a \Delta a; \\
X_a = X_{a0} + X_a^V \Delta V + X_a^H \Delta H + X_a^a \Delta a; \\
P\,cos\,a = P_0\,cos\,a_0 + (P^V\,cos\,a_0)\Delta V + (P^H\,cos\,a_0)\Delta H + \left(P^{\delta_{\text{р}}}\,cos\,a_0\right)\Delta\delta_{\text{р}} + \\
+(P_0 + sin\,a_0)\Delta a \\
P\,cos\,a = P_0\,sin\,a_0 + (P^V\,sin\,a_0)\Delta V + (P^H\,sin\,a_0)\Delta H + \left(P^{\delta_{\text{р}}}\,sin\,a_0\right)\Delta\delta_{\text{р}} + \\
+(P_0 + cos\,a_0)\Delta a \\
mg\sin\Theta = mg\,sin\,\Theta_0 + (mg\,cos\,\Theta_0)\,\Delta\Theta = (mg\,cos\,\Theta_0)\Delta\Theta; \\
mg\,cos\,\Theta = mg\,cos\,\Theta_0 + (mg\,sin\,\Theta_0)\,\Delta\Theta = mg\,cos\,\Theta_0\,; \\
V\,sin\,\Theta = V_0\,sin\,\Theta_0 + (sin\,\Theta_0)\Delta V + (V_0\,cos\,\Theta_0)\,\Delta\Theta = (V_0\,cos\,\Theta_0)\Delta\Theta; \\
mV\dot{\Theta} = mV_0\dot{\Theta} + (mV_0)\,\Delta\dot{\Theta} + \left(m\dot{\Theta}_0\right)\Delta V = mV_0\,\Delta\dot{\Theta}.
\end{gathered}
\tag{5.4}
$$

In the last four equations, it is taken into account that $sin\Theta_0 = 0;\ \dot{\Theta}_0 = 0$.

Substitute the obtained expressions (5.4) into the original system (5.1), subtract from these equations the equation of undisturbed motion (5.2). To write the system of differential equations in the Cauchy form, we divide the first equation by m, the second on mV_0, and the third on I_z.

After summing similar terms, we get the equation of longitudinal motion in small deviations:

$$
\begin{gathered}
\Delta\dot{V} + a_x^{-V}\Delta V + a_x^{-a}\Delta a + a_x^{-\Theta}\Delta\Theta + a_x^{-H}\Delta H = a_x^{-\delta_{\text{р}}}\Delta\delta_{\text{р}}; \\
\Delta\dot{\theta} + a_y^{-V}\Delta V + a_y^{-a}\Delta a + a_y^{-\Theta}\Delta\Theta + a_y^{-H}\Delta H = a_y^{-\delta_{\text{р}}}\Delta\delta_{\text{р}}; \\
\Delta\dot{\omega}_z + a_{m_z}^{-V}\Delta V + a_{m_z}^{-a}\Delta a + a_{m_z}^{-\dot{a}}\Delta\dot{a} + a_{m_z}^{-\omega_z}\Delta\omega_z + a_{m_z}^{-H}\Delta H = a_{m_z}^{-\delta_{\text{в}}}\Delta\delta_{\text{в}}; \\
\Delta\dot{\vartheta} = \Delta\omega_z; \\
\Delta a = \Delta\vartheta - \Delta\Theta; \\
\Delta\dot{H} + a_H^{-V}\Delta V + a_x^{-\Theta}\Delta\Theta = 0.
\end{gathered}
\tag{5.5}
$$

The coefficients of the linearized system of equations have the form:

$$a_x^{-V} = \frac{1}{m}(X_a^V - P^V \cos\alpha_0);\ a_x^{-\alpha} = \frac{1}{m}(X_a^\alpha - P_0\, sin\,\alpha_0);\ a_x^{-\theta} = g\cos\Theta_0\,;$$
$$a_x^{-H} = \frac{1}{m}(X_a^H - P^H\, cos\,\alpha_0);\ a_x^{-\delta_р} = \frac{1}{m}P^{\delta_р}\, cos\,\alpha_0\,;$$
$$a_y^{-V} = -\frac{1}{mV_0}(Y_a^V + P^V \sin a_0);\ a_y^{-\alpha} = \frac{1}{mV_0}(Y_a^\alpha + P_0\, cos\, a_0);$$
$$a_y^{-\Theta} = -\frac{g}{V_0} sin\,\Theta_0\,; a_y^{-H} = -\frac{1}{mV_0}(Y_a^H + P^H\, sin\,\alpha_0);\ a_y^{-\delta_р} = \frac{1}{mV_0}P^{\delta_р}\, sin\,\alpha_0\,; \quad (5.6)$$
$$a_{m_z}^{-V} = -\frac{M_z^V}{I_z}; a_{m_z}^\alpha = -\frac{M_z^\alpha}{I_z};\ a_{m_z}^{\dot\alpha} = -\frac{M_z^{\dot\alpha}}{I_z};\ a_{m_z}^{\omega_z} = -\frac{M_z^{\omega_z}}{I_z};\ a_{m_z}^H = -\frac{M_z^H}{I_z}\ ;$$
$$a_{m_z}^{\delta_в} = -\frac{M_z^{\delta_в}}{I_z}; a_H^{-V} = -\sin\Theta_0\,; a_H^{-\Theta} = -V_0\, cos\,\Theta_0.$$

Coefficients $a_x^{-H}, a_y^{-H}, a_{mz}^{-H}$ cause changes in aerodynamic forces and moments, as well as engine thrust during changes in air density with flight height. With small deviations from the height ΔH components can be neglected $a_x^{-H}\Delta H, a_y^{-H}\Delta H, a_{mz}^{-H}\Delta H,$ which only simplifies the mathematical model because the kinematic equation $\Delta\dot H + a_H^{-V}\Delta V + a_H^{-\Theta}\Delta\Theta = 0$; does not affect the last equations of the system, so they can be considered separately. In addition, the coefficient can be neglected $a_y^{-\delta_p}$, considering its small size.

Let's transform the set of equations (5.5). After differentiating the ratio $\Delta a = \Delta\vartheta - \Delta\Theta$ and substitution in it $\Delta\dot\vartheta = \Delta\omega_z$ can be obtained taking into account the second equation of system (5.5).

$$\Delta\dot\alpha = \Delta\omega_z + a_y^{-V}\Delta V + a_y^{-a}\Delta a + a_y^{-\Theta}\Delta\Theta \quad (5.7)$$

Substituting in $\dot\alpha$ the third equation of system (5.5) and supplementing the system with relation (5.7), we obtain taking into account the assumptions made above:

$$
\begin{gathered}
\dot{V} + a_x^{-V}\Delta V + a_x^{-a}\Delta a + a_x^{-\Theta}\Delta\Theta = a_x^{-\delta_\text{р}}\Delta\delta_\text{р};\ \hat{a} \\
\Delta\dot{\Theta} + a_y^{-V}\Delta V + a_y^{-a}\Delta a + a_y^{-\Theta}\Delta\theta = 0; \\
\Delta\dot{\omega}_z + \hat{a}_{m_z}^{V}\Delta V + \hat{a}_{m_z}^{a}\Delta a + \hat{a}_{m_z}^{\Theta}\Delta\Theta + \hat{a}_{m_z}^{\omega_z}\Delta\omega_z = a_{m_z}^{-\delta_\text{в}}\Delta\delta_\text{в}; \\
\Delta\dot{a} + a_y^{-V}\Delta V + a_y^{-a}\Delta a + a_y^{-\Theta}\Delta\Theta - \Delta\omega_z = 0.
\end{gathered} \tag{5.8}
$$

The coefficients of the third equation of the system (5.8) are calculated according to the formulas:

$$
\begin{gathered}
\hat{a}_{m_z}^{V} = a_{m_z}^{-V} + a_{m_z}^{-\dot{a}}\, a_y^{-V}; \\
\hat{a}_{m_z}^{a} = a_{m_z}^{-\alpha} + a_{m_z}^{-\dot{a}}\, a_y^{-\alpha}; \\
\hat{a}_{m_z}^{\Theta} = a_{m_z}^{-\dot{a}}\, a_y^{-\Theta}; \\
\hat{a}_{m_z}^{\omega_z} = a_{m_z}^{-\omega_z} + a_{m_z}^{-\dot{a}}.
\end{gathered} \tag{5.9}
$$

In the theory of automatic control, it is accepted to write mathematical models in dimensionless form, that is, to enter relative (dimensionless) coordinates. At the same time, it is necessary to first choose the basic values of the variables.

Choosing the value of one radian as the base value for the angular parameters, and the value for the flight speed V_0, we will get:

$$
\bar{V} = \frac{\Delta V}{V_0}; \bar{\Theta} = \Delta\Theta; \bar{\alpha} = \Delta\alpha; \bar{\vartheta} = \Delta\vartheta; \overline{\delta_\text{в}} = \Delta\delta_\text{в}; \overline{\delta_\text{р}} = \Delta\delta_\text{р};
$$

In the future, we will omit the hyphen above the designation of dimensionless parameters.

To move to dimensionless coordinates, multiply and divide each term that holds ΔV and derived from ΔV, on V_0, and divide both parts of the first equation by V_0. As a result, we get:

$$
\begin{aligned}
&\dot{V} + a_x^V V + a_x^\Theta \Theta + a_x^\alpha \alpha = a_x^{\delta_\text{р}} \delta_\text{р};\\
&\dot{\theta} + a_y^V V + a_y^\Theta \Theta + a_y^\alpha \alpha = 0;\\
&\dot{\omega}_z + a_{m_z}^V V + a_{m_z}^\Theta \Theta + a_{m_z}^{\omega_z} \omega_z + a_{m_z}^\alpha \alpha = a_{m_z}^{\delta_\text{в}} \delta_\text{в};\\
&\dot{\alpha} - a_y^V V - a_y^\Theta \Theta - \omega_z - a_y^\alpha \alpha = 0.
\end{aligned} \qquad (5.10)
$$

The coefficients of the mathematical model (5.10), taking into account (5.6), (5.9) and the ratios for aerodynamic forces and moments, have the form:

$$
\begin{aligned}
&a_x^V = a_x^{-V} = \frac{1}{\tau_a}\left(C_{x_a} + V_0 \frac{c_{x_a}^V}{2}\right) - \frac{P^V \cos\alpha_0}{m};\ a_x^{-\Theta} = \frac{a_x^{-\Theta}}{V_0} = \frac{g\cos\Theta_0}{V_0};\\
&a_x^\alpha \alpha = \frac{a_x^{-\alpha}}{V_0} = \frac{c_{x_a}^\alpha}{2\tau_a} + \frac{P_0 \sin\alpha_0}{mV_0};\ a_x^{\delta_\text{р}} = \frac{a_x^{-\delta_\text{р}}}{V_0} = \frac{P^{\delta_\text{р}}}{mV_0}\cos\alpha_0;\\
&a_y^V = a_y^{-V} V_0 = -\frac{1}{\tau_a}\left(C_{y_a} + \frac{V_0}{2}\, c_{y_a}^V\right) - \frac{P^V \sin\alpha_0}{m};\\
&a_y^\alpha = a_y^{-\alpha} = -\left(\frac{C_{y_a}^\alpha}{2\tau_a} + \frac{P_0 \cos\alpha_0}{mV_0}\right);\ a_y^\Theta = a_y^{-\Theta} = -\frac{g\cos\Theta_0}{V_0};\\
&a_{m_z}^V = \hat{a}_{m_z}^V V_0 = -x\left(m_z^V V_0 + 2m_z + \frac{b_A}{V_0} m_z^{\bar{\dot{\alpha}}}\, a_y^V\right);\ a_{m_z}^{\delta_\text{в}} = a_{m_z}^{-\delta_\text{в}} = x\, m_z^{\delta_\text{в}};\\
&a_{m_z}^\alpha = \hat{a}_{m_z}^\alpha = -x\left(m_z^\alpha + \frac{b_A}{V_0} m_z^{\bar{\dot{\alpha}}}\, a_y^\alpha\right);\ a_{m_z}^{\omega_z} = \hat{a}_{m_z}^{\omega_z} = -x\frac{b_A}{V_0}\left(m_z^{\overline{\omega_z}} + m_z^{\bar{\dot{\alpha}}}\right);\\
&a_{m_z}^\Theta = \hat{a}_{m_z}^\Theta = -x\,\frac{b_A}{V_0} m_z^{\bar{\dot{\alpha}}}\, a_y^\Theta;\ \tau_a = \frac{m}{\rho_0 V_0 S};\ x = \frac{\rho_0 V_0^2 S b_A}{2I_z}.
\end{aligned} \qquad (5.11)
$$

Here $m_z^{\bar{\omega}_z}$ and $m_z^{\bar{\dot{\alpha}}}$ derivatives of dimensionless angular velocities

$$
\bar{\dot{\alpha}} = \frac{b_A}{V_0}\dot{\alpha};\ \overline{\omega_z} = \frac{b_A}{V_0}\omega_z.
$$

Next, applying the Laplace transform to system (5.10) with zero initial conditions, we obtain a mathematical model of the longitudinal motion of the aircraft in operational form:

$$
\begin{gathered}
(p + a_x^V)\, V(p) + a_x^{\Theta}\Theta(p) + a_x^{\alpha}\alpha(p) = a_x^{\delta_{\text{p}}}\delta_{\text{p}}(p);\\
a_y^V\, V(p) + \left(p + a_y^{\Theta}\right)\Theta(p) + a_y^{\alpha}\alpha(p) = 0;\\
a_{m_z}^V\, V(p) + a_{m_z}^{\Theta}\Theta(p) + \left(p + a_{m_z}^{\omega_z}\right)\omega_z(p) + a_{m_z}^{\alpha}\alpha(p) = a_{m_z}^{\delta_{\text{в}}}\delta_{\text{в}}(p);\\
-a_y^V\, V(p) - a_y^{\Theta}\Theta(p) - \omega_z(p) - \left(p - a_y^{\alpha}\right)\alpha(p) = 0.
\end{gathered} \tag{5.12}
$$

When deriving the equations of longitudinal short-period motion, the independence of this motion from the flight speed is assumed. Note that for programmed horizontal flight $sin\Theta_0 = 0$, and, therefore, the coefficients:

$a_y^{\Theta} = -\frac{g}{V_0}\, sin\,\Theta_0 = 0;\; a_{m_z}^{\Theta} = -x\frac{b_A}{V_0} m_z^{\bar{\dot{\alpha}}}\, a_y^{\Theta} = 0.$

Taking into account these conditions, the system of equations describing the longitudinal short-period movement takes the form:

$$
\begin{gathered}
p\Theta(p) + a_y^{\alpha}\alpha(p) = 0;\\
\left(p + a_{m_z}^{\alpha}\right)\omega_z(p) + a_{m_z}^{\alpha}\alpha(p) = a_{m_z}^{\delta_{\text{в}}}\delta_{\text{в}}(p);\\
-\omega_z(p) - \left(p - a_y^{\alpha}\right)\alpha(p) = 0.
\end{gathered} \tag{5.13}
$$

The first equation of the system (5.13) does not affect the others, so it can be considered separately. The characteristic equation corresponds to the system of two remaining equations:

$A(p) = p^2 + a_1 p + a_0,$

Where $a_1 = a_{m_z}^{\omega_z} - a_y^{\alpha}; a_0 = a_{m_z}^{\alpha} - a_{m_z}^{\omega_z} a_y^{\alpha}.$

In long-periodic movement, the angle of attack practically does not change, so it can be assumed $pa \approx 0$ then $\omega_z \approx p\theta$, and the angle of inclination of the trajectory changes slowly, therefore, it is assumed $p\omega_z = p^{2\theta} \approx 0$. With such assumptions, the system of equations describing the long-periodic movement takes the form:

$$
\begin{gathered}
(p + a_x^V)\, V(p) + a_x^{\Theta}\Theta(p) + a_x^{\alpha}\alpha(p) = a_x^{\delta_{\text{p}}}\delta_{\text{p}}(p);\\
a_y^V\, V(p) + p\Theta(p) + a_y^{\alpha}\alpha(p) = 0;\\
a_{m_z}^V\, V(p) + a_{m_z}^{\omega_z} p\Theta(p) + a_{m_z}^{\alpha}\alpha(p) = a_{m_z}^{\delta_{\text{в}}}\delta_{\text{в}}(p).
\end{gathered}
$$

The characteristic equation corresponds to this system.

$N(p) = n_2 p^2 + n_1 p + n_0,$

Where: $n_2 = a_{m_z}^{\alpha}; n_1 = a_{m_z}^{\alpha} a_x^V - a_x^{\alpha}\, a_{m_z}^V; n_0 = a_x^{\theta}\left(a_{m_z}^V a_y^{\alpha} - a_{m_z}^{\alpha}\, a_y^V\right).$

Thus, the longitudinal motion of the aircraft, described by the system of equations (5.12), is divided into two components, which are separated by time and frequency, which makes it possible to study them separately.

5.2 Calculation of the coefficients of the mathematical model of longitudinal movement.

Coefficients of the mathematical model of longitudinal movement [18] are calculated based on its aerodynamic parameters and some weight and geometric characteristics. Longitudinal movements are described by a linearized system of equations. To calculate the coefficients of these equations, it is necessary to know some weight and geometric characteristics of the aircraft, as well as its aerodynamic coefficients.

Below are the characteristics of the UAV, on the basis of which the coefficients of the mathematical model of longitudinal movement were calculated.

Geometric dimensions of the UAV:

1.Wing area $S = 50\ m^2$.

2.Average aerodynamic chord $b_A = 6m$.

UAV weight characteristics:

1. Weight of aircraft $m = 30000\ kg$.

2. Moment of inertia $I_z = 500000\ N{\cdot}s^2{\cdot}m$.

Aerodynamic characteristics of UAVs:

1. $m_Z^{\delta_{\text{В}}} = -1{,}7;$

2. $m_Z^{\alpha} = -0{,}37;$

3. $m_Z^{\omega z} = -1.5;$

4. $m_Z^{\dot{\alpha}} = -0{,}41.$

Flight parameters:

The speed of the UAV relative to the ground $V = 200\frac{m}{s}$;

Flight height H=1000m.

Auxiliary coefficients:

Coefficient of aerodynamic lifting power $c_{ya} = 0{,}63$;

Inductance coefficient $A = 0.125$;

The drag force coefficient at zero lift and the wave resistance of air condensation $c_{x0} = 0.018$;

The coefficient of dependence of the aerodynamic pitch moment on the flight speed $m_Z^{M} = -0{,}075$;

Engine thrust at a given speed $P_1 = 0.99$;

We calculate the drag force coefficients:

$c_{xa} = c_{x0} + A * c_{ya}{}^2 = 0{,}068;\ c_{ya}^V = 3.747 * 10^{-3}$;

$c_{xa}^{\alpha} = 2 * A * c_y^{\alpha} = 1{,}15;\ A^V = 4{,}527 * 10^{-4}$;

$c_{x0}^V = 3.25 * 10^{-5};\ c_{xa}^V = c_{x0}^V + A^V * c_{ya}^2 + 2 * A * c_{ya}^V = 1.149 * 10^{-3}$;

Calculation of main coefficients:

$\alpha = \frac{2*m*g}{c_{ya}*\rho_H*V^2*S} = 0.047;\ \Theta = 0.$

1. $a_x^V = \frac{1}{\tau_a}\left(c_{xa} + \frac{V*c_{xa}}{2}\right) - \frac{P^V*cos(\alpha)}{m} = 0.01318;$

2. $a_x^{\Theta} = g * \frac{cos(\Theta)}{V} = 0.04905;$

3. $a_x^{\alpha} = \frac{c_{xa}^{\alpha}}{2*\tau_a} + \frac{P_0*sin(\alpha)}{m*V} = 0.08745;$

4. $P_{\delta_p} = 1;\ a_x^{\delta_p} = \frac{P_{\delta_p}}{m*V} * cos(\alpha) = 0.0364;$

5. $a_y^V = \frac{-1}{\tau_a}\left(c_{ya} + \frac{V*c_{ya}^V}{2}\right) - \frac{P^V*sin(\alpha)}{m} = -0.01854;$

6. $a_y^{\alpha} = -\left(\frac{c_{ya}}{2*\tau_a} + \frac{P_0*cos(\alpha)}{m*V}\right) = -0.8907;$

7. $a_{y}^{\Theta} = -g * \frac{sin(\Theta)}{V} = 0;$

8. $a_{m_{Z}}^{V} = -x * \left(m_{z}^{V} * V + 2 * m_{z} + \frac{b_{A}}{V} * m_{z}^{\dot{\alpha}} * a_{y}^{V}\right) = -0.03043;$

9. $a_{m_{Z}}^{\delta_{в}} = x * m_{z}^{\delta_{в}} = -23.35;$

10. $a_{m_{Z}}^{\alpha} = -x * \left(m_{a}^{\alpha} + \frac{b_{A}}{V} * m_{z}^{\dot{\alpha}} * a_{y}^{\alpha}\right) = 4.765;$

11. $a_{m_{z}}^{\omega_{z}} = -x * \frac{b_{A}*(m_{z}^{\omega_{z}}+m_{z}^{\dot{\alpha}})}{V} = 0.7646;$

12. $a_{m_{z}}^{\Theta} = 0.$

5.3 Synthesis of automatic control loops according to the selected control law

The synthesis of automatic control loops is carried out according to simplified mathematical models, for example, using structural diagrams obtained on the basis of transfer functions.

5.3.1 Transfer functions and structural diagrams of the mathematical model of longitudinal motion

Transfer function $W_{out}^{in}(p)$ is the image ratio of the original value $U_{out}(p)$ to the image of the input value $U_{in}(p)$ at zero initial conditions. The peculiarity of the transfer functions of the aircraft as a control object is that the ratio of images is taken with the inverted sign. This is due to the fact that in aerodynamics it is accepted as positive deviations of control bodies to consider deviations that create negative increments in the angular parameters of the aircraft's motion. That is why the negative sign is before the transfer function.

$$W_{\Theta}^{\text{B}}(p) = -\frac{\Theta(p)}{\delta_{\text{B}}(p)}$$

In the analysis and synthesis of control contours of angular longitudinal movements, the model of short-periodic movement is usually used. The solutions correspond to the system describing the short-period longitudinal movement:

$$\omega_z(p) = \frac{a_{m_z}^{\delta_B}(p - a_y^\alpha)}{p^2 + a_1 p + a_0}\delta_B(p)$$
$$\alpha(p) = \frac{a_{m_z}^{\delta_B}}{p^2 + a_1 p + a_0}\delta_B(p) \qquad (5.14)$$

Where: $p^2 + a_1 p + a_0$ – characteristic polynomial with coefficients $a_1 = a_{m_z}^{\omega_z} - a_y^\alpha,\ a_0 = a_{m_z}^\alpha - a_y^\alpha a_{m_z}^{\omega_z}$.

Let's introduce a notation:

$$\omega_\alpha^2 = a_0;\ \xi_\alpha = \frac{a_1}{2\sqrt{a_0}};\ T_\theta = -\frac{1}{a_y^\alpha};\ K_\alpha^B = -\frac{a_{m_z}^{\delta_B}}{\omega_\alpha^2} \qquad (5.15)$$

Taking into account these relations, we obtain the transfer functions relating the angle of attack, the pitch angle and the angle of inclination of the trajectory, as well as the pitch speed with the deviation of the pitch control body:

$$W_\alpha^B(p) = \frac{\alpha(p)}{-\delta_B(p)} = \frac{K_\alpha^B \omega_\alpha^2}{p^2 + 2\xi_\alpha \omega_\alpha p + \omega_\alpha^2}; \qquad (5.16)$$

$$W_{\omega_z}^B(p) = \frac{\omega_z(p)}{-\delta_B(p)} = \frac{K_{\dot\vartheta}^B \omega_\alpha^2 (T_\theta p + 1)}{p^2 + 2\xi_\alpha \omega_\alpha p + \omega_\alpha^2}; \qquad (5.17)$$

$$W_\vartheta^B(p) = W_{\omega_z}^B(p)\frac{1}{p} = \frac{\vartheta(p)}{-\delta_B(p)} = \frac{K_{\dot\vartheta}^B \omega_\alpha^2 (T_\theta p + 1)}{(p^2 + 2\xi_\alpha \omega_\alpha p + \omega_\alpha^2)p}; \qquad (5.18)$$

$$W_{\theta}^{\text{B}}(p) = W_{\vartheta}^{\text{B}}(p) - W_{\alpha}^{\text{B}}(p) = \frac{\theta(p)}{-\delta_{\text{B}}(p)} = \frac{K_{\dot{\vartheta}}^{\text{B}}\omega_{\alpha}^{2}}{(p^{2} + 2\xi_{\alpha}\omega_{\alpha}p + \omega_{\alpha}^{2})p}; \qquad (5.19)$$

Where: $K_{\dot{\vartheta}}^{\text{B}} = -\frac{a_{m_z}^{\delta_{\text{B}}}}{\omega_{\alpha}^{2}} a_{y}^{\alpha} = -\frac{a_{m_z}^{\delta_{\text{B}}}}{\omega_{\alpha}^{2} T_{\theta}}$.

Let's determine the transfer function of the aircraft under normal overload n_y, which plays an important role in flight control processes.

The normal acceleration can be calculated using the formula:

$$j_{y_a} = \frac{Y_a + P\, sin\, \alpha}{m} \qquad (5.20)$$

Moving on to the relative coordinates in increments, we get

$$\bar{j}_{y_a} = \frac{\Delta j_{y_a}}{g} = n_{y_a} \approx \frac{1}{g} \frac{Y_a^{\alpha} + P\, cos\, \alpha}{m} \alpha \qquad (5.21)$$

where the derivatives are taken at the point corresponding to undisturbed motion. Given that $Y_a^{\alpha} = c_{y_a}^{\alpha} \frac{\rho V^2}{2} S$, and our found coefficients (5.11), we get the formula for normal overload:

$$n_{y_a} \approx -\frac{V}{g} a_y^{\alpha}\, \alpha = \frac{V}{g T_{\theta}} \alpha \qquad (5.22)$$

Where: $\alpha = \bar{\alpha};\ T_{\theta} = -\frac{1}{a_y^{\alpha}}$; V – undisturbed flight speed.

Taking into account relations (5.16), (5.22), we obtain the transfer function for normal overload:

$$W_{n_y}^{\text{B}}(p) = \frac{n_y(p)}{-\delta_{\text{B}}(p)} = \frac{K_{n_y}^{\text{B}}\omega_\alpha^2}{p^2 + 2\xi_\alpha\omega_\alpha p + \omega_\alpha^2} \tag{5.23}$$

Where: $K_{n_y}^{\text{B}}(p) = K_\alpha^{\text{B}}\frac{V}{gT_\theta}$ – overload proportionality factor.

Thus, longitudinal angular movements are characterized by three parameters:

– frequency of non-damping short-period oscillations:

$$\omega_\alpha = \sqrt{a_0} = \sqrt{a_{m_z}^\alpha - a_y^\alpha a_{m_z}^{\omega_z}} \tag{5.24}$$

– by the logarithmic decrement of attenuation:

$$\xi_\alpha = \frac{a_1}{2\omega_\alpha} = \frac{a_{m_z}^{\omega_z} - a_y^\alpha}{2\omega_\alpha} \tag{5.25}$$

– time constant:

$$T_\theta = -\frac{1}{a_y^\alpha} \tag{5.26}$$

Frequency of non-damping short-period oscillations ω_α proportional to the flight speed V and decreases with flight height. Quantity ω_α approximately proportional $\sqrt{\rho}$. Attenuation decrement ξ_α does not depend on the speed of the flight, but changes with the height of the flight. Damping of short-period oscillations is also proportional $\sqrt{\rho}$. $K_{\dot{\vartheta}}^{\text{B}}$ – gear ratio from pitch speed with the deviation of the pitch control body.

In this way, we can calculate the parameters ω_α, ξ_α, T_θ, $K_{\dot{\vartheta}}^{\text{B}}$. So:

$$\omega_\alpha = \sqrt{a_0} = \sqrt{a_{m_z}^{\alpha} - a_y^{\alpha} a_{m_z}^{\omega_z}} = \sqrt{4{,}765 - (-0{,}681)} = \sqrt{5{,}446} = 2{,}33$$

$$\xi_\alpha = \frac{a_1}{2\omega_\alpha} = \frac{a_{m_z}^{\omega_z} - a_y^{\alpha}}{2\omega_\alpha} = \frac{1{,}6553}{4{,}66} = 0{,}3552$$

$$T_\theta = -\frac{1}{a_y^{\alpha}} = -\frac{1}{-0{,}8907} = 1{,}1227$$

$$K_{\dot\vartheta}^{\text{B}} = -\frac{a_{m_z}^{\delta_\text{B}}}{\omega_\alpha^2} a_y^{\alpha} = -\frac{a_{m_z}^{\delta_\text{B}}}{\omega_\alpha^2 T_\theta} = -\frac{-23{,}35}{6{,}095} = 3{,}831$$

When calculating the transfer ratios of the selected laws of automatic control, we will use the sequential synthesis of control circuits starting from stability and controllability circuits.

5.3.2 Synthesis of the pitch damper

The short-period longitudinal movement at pitch speed is described by a transfer function that has the form:

$$W_{\dot\vartheta}^{\text{B}}(p) = \frac{K_{\dot\vartheta}^{\text{B}} \omega_\alpha^2 (T_\theta p + 1)}{p^2 + 2\xi_\alpha \omega_\alpha p + \omega_\alpha^2},$$

where $K_{\dot\vartheta}^{\text{B}} = K_{\omega_z}^{\text{B}} = K_\alpha^{\text{B}} T_\theta^{-1}$.

Figure 5.1 shows the structural diagram of the damping circuit.

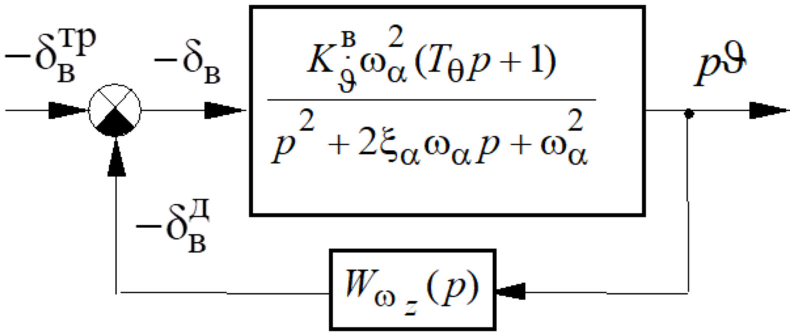

Fig. 5.1 Structural diagram of the damping circuit

Here for the selected control law $\delta_\text{B}^{\text{Д}} = \text{K}_{\dot\vartheta} \text{p}\vartheta$, and is a signal of contours of the highest level of the hierarchy.

In our case, the feedback transfer function in the damping circuit of short-period longitudinal movements has the form:

$$W_{\omega_z}(p) = K_{\dot{\vartheta}} \tag{5.27}$$

Let's determine the equivalent transfer function of the closed circuit " aircraft + damper":

$$W_{\dot{\vartheta}_д}^{в}(\mathrm{p}) = \frac{W_{\dot{\vartheta}}^{в}(\mathrm{p})}{1 + W_{\dot{\vartheta}}^{в}(\mathrm{p}) W_{\omega\, z}(\mathrm{p})} =$$

$$= \frac{K_{\dot{\vartheta}}^{в}\omega_{\alpha}^{2}(T_{\theta}\mathrm{p} + 1)}{\mathrm{p}^{2} + (2\xi_{\alpha}\omega_{\alpha} + K_{\dot{\vartheta}}^{в}\omega_{\alpha}^{2}T_{\theta}K_{\dot{\vartheta}})\mathrm{p} + (\omega_{\alpha}^{2} + K_{\dot{\vartheta}}^{в}\omega_{\alpha}^{2}K_{\dot{\vartheta}})}.$$

Let's mark: $\omega_{\alpha д}^{2} = (\omega_{\alpha}^{2} + K_{\dot{\vartheta}}^{в}\omega_{\alpha}^{2}K_{\dot{\vartheta}})$, $2\xi_{\alpha д}\omega_{\alpha д} = (2\xi_{\alpha}\omega_{\alpha} + K_{\dot{\vartheta}}^{в}\omega_{\alpha}^{2}T_{\theta}K_{\dot{\vartheta}})$, $K_{\dot{\vartheta}_д}^{в}\omega_{\alpha д}^{2} = K_{\dot{\vartheta}}^{в}\omega_{\alpha}^{2}$

Then $\omega_{\alpha д} = \omega_{\alpha}\sqrt{1 + K_{\dot{\vartheta}}^{в}K_{\dot{\vartheta}}}$; $\xi_{\alpha д} = \frac{(\xi_{\alpha} + 0{,}5K_{\dot{\vartheta}}^{в}\omega_{\alpha}T_{\theta}K_{\dot{\vartheta}})}{\sqrt{1 + K_{\dot{\vartheta}}^{в}K_{\omega\, z}}} \approx \xi_{\alpha} + 0{,}5K_{\dot{\vartheta}}^{в}\omega_{\alpha}T_{\theta}K_{\dot{\vartheta}}$; $K_{\dot{\vartheta}_д}^{в} = \frac{K_{\dot{\vartheta}}^{в}\omega_{\alpha}^{2}}{\omega_{\alpha д}^{2}} = \frac{K_{\dot{\vartheta}}^{в}}{1 + K_{\dot{\vartheta}}^{в}K_{\dot{\vartheta}}}$.

Taking into account the notations made, the equivalent transfer function of the closed circuit "aircraft + damper" takes the form:

$$W_{\dot{\vartheta}_д}^{в}(P) = \frac{K_{\dot{\vartheta}_д}^{в}\omega_{\alpha д}^{2}(T_{\theta}P + 1)}{P^{2} + 2\xi_{\alpha д}\omega_{\alpha д}P + \omega_{\alpha д}^{2}}.$$

Attenuation decrement ξ_{α} depends on the flight modes, and the choosen attenuation decrement $\xi_{\alpha_д}$ will almost always equal 0,7..1.0. Usually the condition is fulfilled $(1 + K_1 K_{\omega})^{0{,}5} \approx 1$ on all flight modes and then from the expression for $\xi_{\alpha_д}$, we will obtain the calculation formula for the coefficient of rigid feedback, which will provide the specified damping:

$$K_{\dot{\vartheta}} \approx \frac{\xi_{\alpha_д} - \xi_{\alpha}}{0{,}5\omega_{\alpha}K_{\dot{\vartheta}}^{B}T_{\theta}} \tag{5.28}$$

Let's calculate $K_{\dot{\vartheta}}$ at $\xi_{\alpha_д} = 0{,}7$ and $\xi_{\alpha_д} = 1$. So:

$$K_{\dot{\vartheta}} \approx \frac{0{,}7 - \xi_\alpha}{0{,}5\omega_\alpha K_{\dot{\vartheta}}^{\text{B}} T_\theta} = \frac{0{,}3448}{5{,}01} = 0{,}0688$$

$$K_{\dot{\vartheta}} \approx \frac{1 - \xi_\alpha}{0{,}5\omega_\alpha K_{\dot{\vartheta}}^{\text{B}} T_\theta} = \frac{0{,}6448}{5{,}01} = 0{,}128$$

We model the internal circuit (damping) in the Simulink environment of the MATLAB mathematical modeling package. The diagram of the modeling process looks like (Fig. 5.2), and the simulation results are shown in Fig. 5.3.

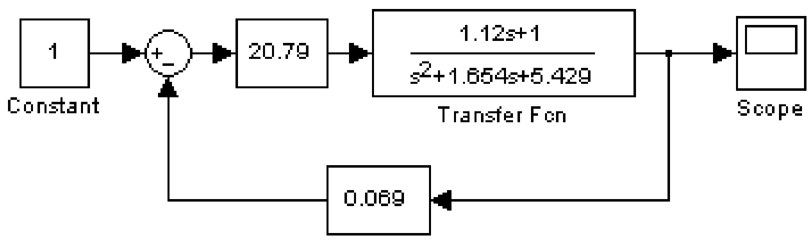

Fig. 5.2 Diagram of the modeling process

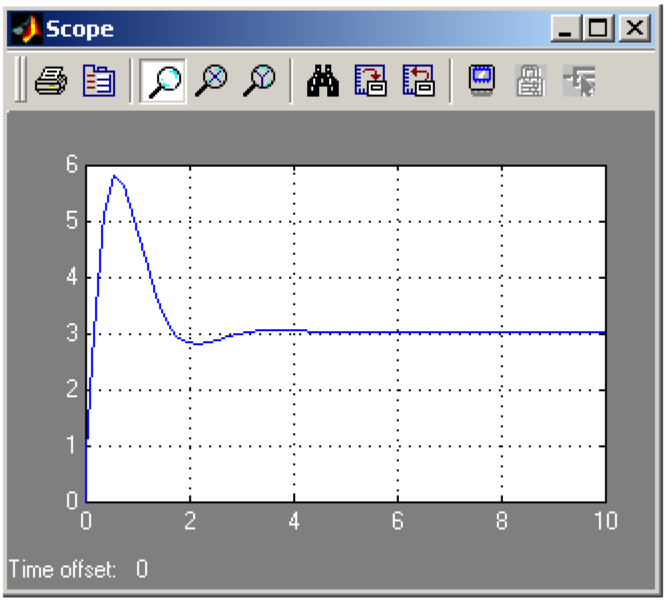

Fig. 5.3 Result of the modelling process with damping circuit

Having modeled the internal circuit (damping), we obtained the results (Fig. 5.3), from which it can be seen that $K_{\dot{\vartheta}}$ is calculated correctly.

5.3.3 Pitch loop synthesis with hard feedback

A hard-feedback pitch autopilot control law (AP϶HF) can be represented as:

$$\delta_{\text{в}} = K_{\vartheta}(\vartheta - \vartheta_3) + K_{\dot{\vartheta}} p \vartheta \qquad (5.29)$$

where ϑ_3– a given value of the pitch angle.

Structural diagram of the system "aircraft – AP϶", that implements the control law (5.29), is shown in Fig. 5.4. The previously synthesized damping circuit is used as an internal circuit in the pitch angle control channel.

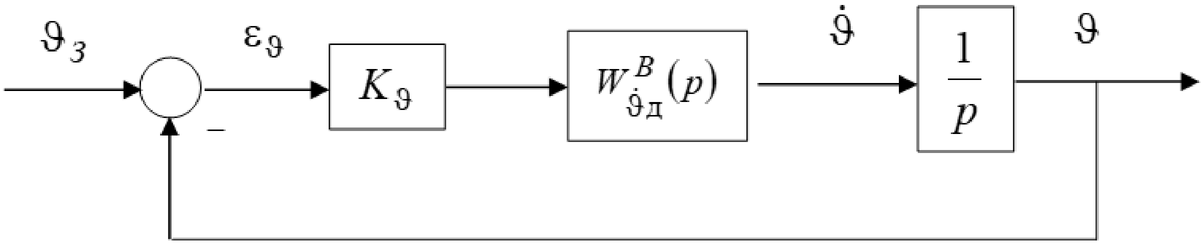

Fig. 5.4 Structural diagram of the system "aircraft – AP϶"

Let's write down the transfer function for the open circuit of the system:

$$W_{\vartheta}(p) = \frac{K_y(T_\theta p + 1)}{p\left(p^2 + 2\xi_{\alpha_д}\omega_{\alpha_д} p + \omega^2_{\alpha_д}\right)} \qquad (5.30)$$

where $K_y = K_\vartheta K^{\text{В}}_{\dot{\vartheta}_д} \omega^2_{\alpha_д}$

In fig. Figure 5.5 shows the asymptotic logarithmic amplitude-frequency characteristic (Bode daigram) of the open system (5.30):

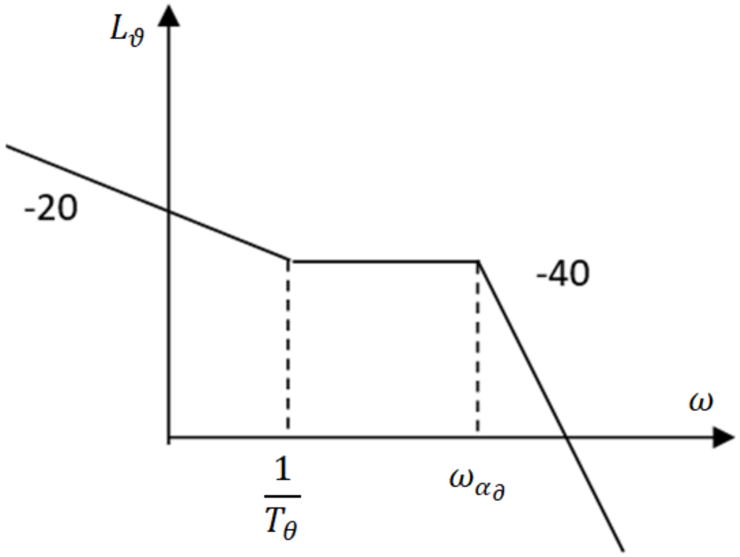

Fig. 5.5 Bode diagram

It is known that for a good quality of the transient process, the Bode diagram of an open system should have a slope of –20 dB/dec at the cutoff frequency. But as can be seen from fig. 5.5, the slope of the Bode diagram in the low-frequency region is equal to –40 dB/dec. Therefore, the cutoff frequency can be placed both to the left and to the right of the frequency $\omega_\theta = \frac{1}{T_\theta}$.

If $\omega_{\text{зр}}$ choose a lower frequency than ω_θ, then it is necessary to ensure the fulfillment of the relationship $\omega_{\text{зр}} = 0{,}9T_\theta^{-1}$. This will allow you to have the maximum cutoff frequency, that is, the minimum time of the transition process.

So, on the one side $\omega_{\text{зр}} = K_\vartheta K_{\dot{\vartheta}_\text{д}}^{\text{В}}$, and on the other – $\omega_{\text{зр}} = 0{,}9T_\theta^{-1}$.

Let's compare the two parts:

$\frac{1}{0{,}9T_\theta} = K_\vartheta K_{\dot{\vartheta}_\text{д}}^{\text{В}}$,

From here we have:

$$K_\vartheta = \frac{1}{0{,}9T_\theta K_{\dot{\vartheta}_\text{д}}^{\text{В}}} \tag{5.31}$$

Taking into account that $K_{\vartheta_Д}^{В} = \frac{K_{\vartheta}^{В}}{1+K_{\vartheta}^{В} K_{\dot{\vartheta}}} = \frac{3,83}{1,264} = 3,03$, we can find K_{ϑ}. That is,

$$K_{\vartheta} = \frac{1}{0,9 T_{\theta} K_{\vartheta_Д}^{В}} = \frac{1}{3,05} = 0,32$$

We model the pitch contour in the Simulink environment of the MATLAB mathematical modeling package. The diagram of the modeling process looks like (Fig. 5.6).

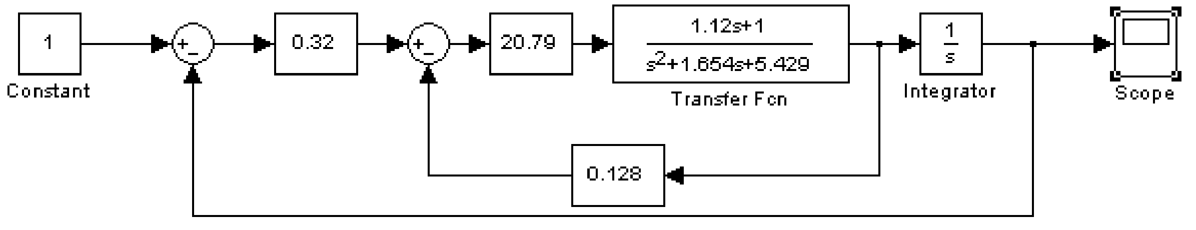

Рис. 5.6 Diagram of the modeling process of the pitch contour

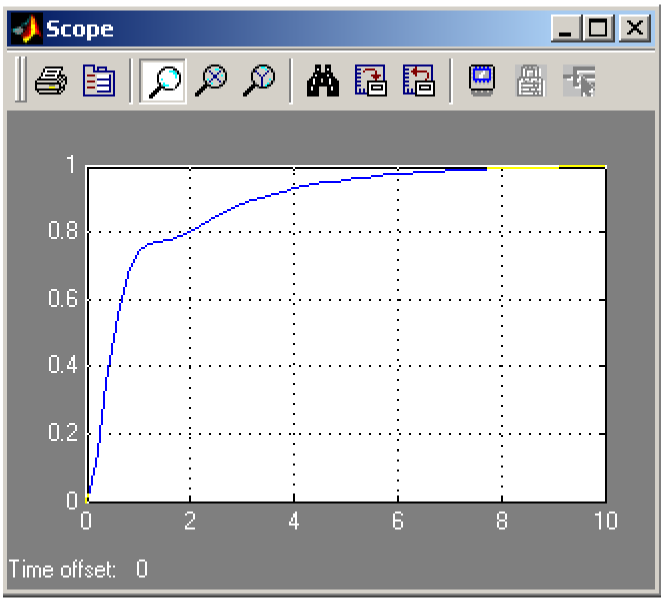

Рис. 5.7 Result of the modelling process of the pitch contour

Having modeled the pitch contour, we obtained the results shown in Fig. 5.7, from which it is clear that K_{ϑ} is calculated correctly.

5.3.4 Synthesis of the UAV flight height control circuit

Forming the feedback from the flight height, we will get the height control circuit. The structural diagram of the flight height control circuit is shown in fig. 5.8:

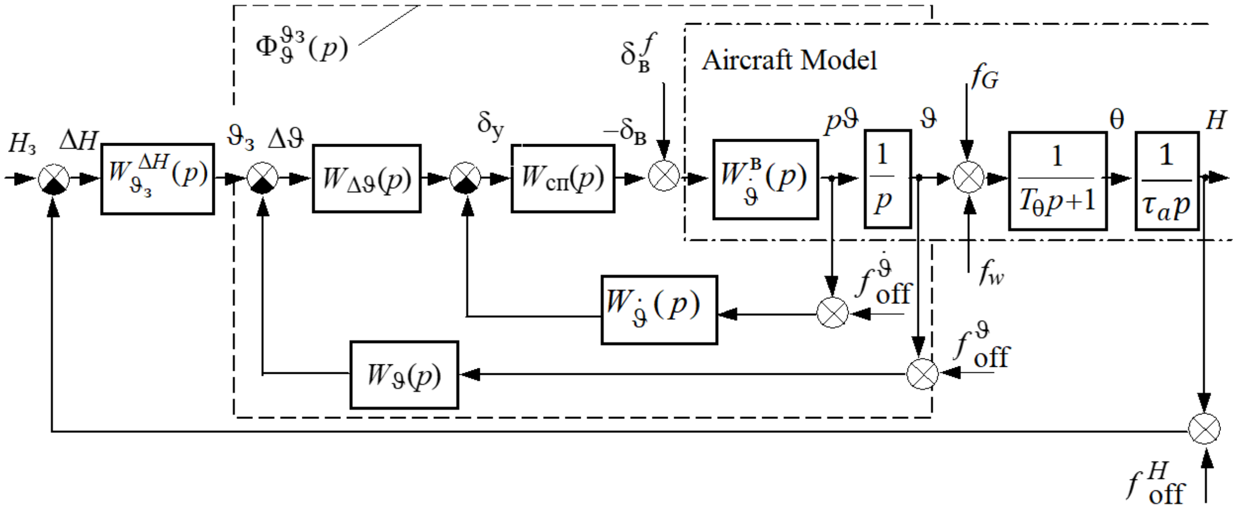

Fig. 5.8 Structural diagram of the flight height control circuit

Let's fold the structural diagram, replacing the closed internal circuit - the pitch circuit with an equivalent transfer function, and we will reduce the disturbances acting inside the closed pitch circuit to its input, using the rules of transformation of structural diagrams. In this form, the structural diagram of the flight height control circuit is shown in fig. 5.9:

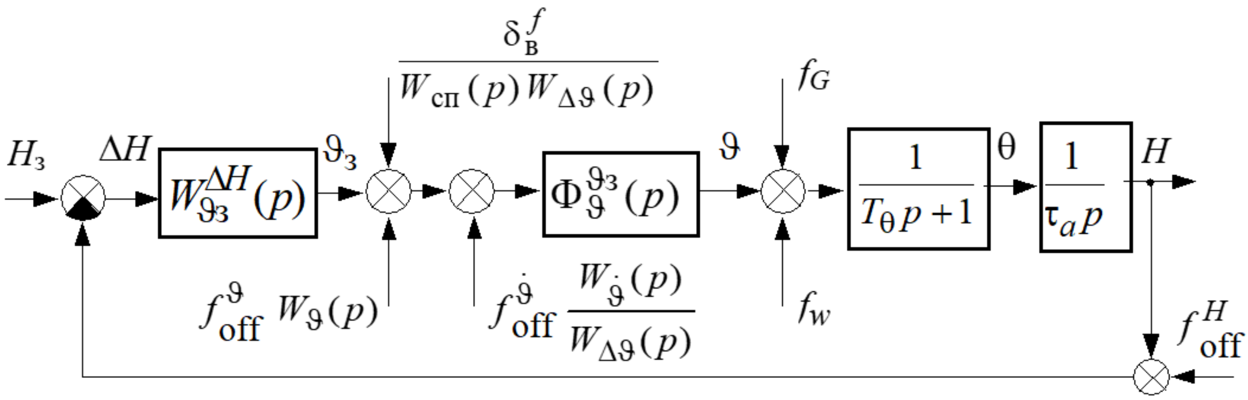

Fig. 5.9 Simplified structural diagram of the flight height control circuit

Most often, a static pitch autopilot with hard feedback is used as an internal altitude control loop ($W_{сп}(p) = 1$), which implements the control law:

$$\delta_в = K_\vartheta(\vartheta - \vartheta_з) + K_{\dot\vartheta} p\vartheta.$$

By ϑ is meant the deviation of the pitch angle from the program – the pitch angle of horizontal flight. When controlling the flight height, the given (relative to the software) value of the pitch angle is formed by the transfer function $W_{\vartheta_з}^{\Delta H}(p)$ under different laws.

With proportional regulation – APϑHF (*H*):

$$\vartheta_з = \frac{K_H}{K_\vartheta}(H_з - H);$$

$$W_{\vartheta_з}^{\Delta H}(p) = \frac{K_H}{K_\vartheta} \qquad (5.32)$$

The control law for such case can be written in the form:

$$\delta_в = K_\vartheta \vartheta + K_H(H - H_з) + K_{\dot\vartheta} p\vartheta.$$

For the system with APϑHF after the transformation by the bandpass filter is equal to:

$$\Phi_\vartheta^{\vartheta_з}(p) = \frac{K_\vartheta\, K_{\dot\vartheta}^{В}\, \omega_\alpha^2 (T_\theta p + 1)}{(p + \omega_{ж_1})(p^2 + 2\xi_{ж_2}\, \omega_{ж_2} p + \omega_{ж_2}^2)} \qquad (5.33)$$

Using the structural diagram shown in Fig. 5.9 and the transfer functions (5.32), (5.33), we write the transfer function of the open trajectory contour:

$$W_H(p) = \frac{K_H\, K_{\dot\vartheta}^{В}\, \omega_\alpha^2\, \tau_\alpha^{-1}}{(p + \omega_{ж_1})(p^2 + 2\xi_{ж_2}\, \omega_{ж_2} p + \omega_{ж_2}^2)} \qquad (5.34)$$

Bode diagram, which corresponds to the transfer function (5.34) is shown in Fig.5.10. That is, $\omega_{зр} = K_H K^{В}_{\dot{\vartheta}_д} \omega_\alpha^2 \tau_\alpha^{-1}$ (assume, that $\tau = 1$) and

$\omega_{зр} = 0.25\omega_{ж_1} = 0.125\frac{1}{T_\theta}$.

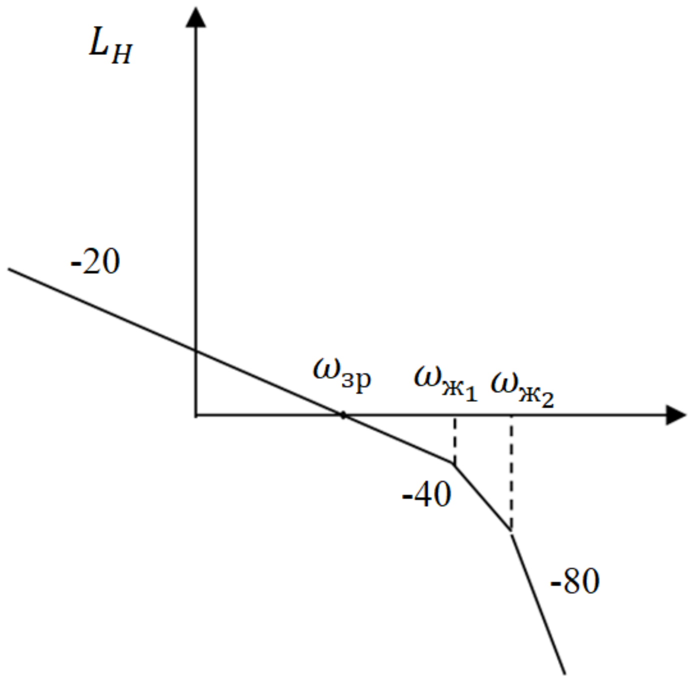

Fig. 5.10 Bode diagram of the flight height control circuit transfer function

From here $\frac{0.125}{T_\theta} = K_H K^{В}_{\dot{\vartheta}_д} \omega_\alpha^2 \tau_\alpha^{-1}$,

$$K_H = \frac{0.125}{K^{В}_{\dot{\vartheta}} \omega_\alpha^2 \tau_\alpha^{-1} T_\theta} = 0.048 \qquad (5.35)$$

We model the UAV altitude control circuit in the Simulink environment of the MATLAB mathematical modeling package. The diagram of the modeling process looks like (Fig. 5.11), and the simulation results are shown in Fig. 5.12.

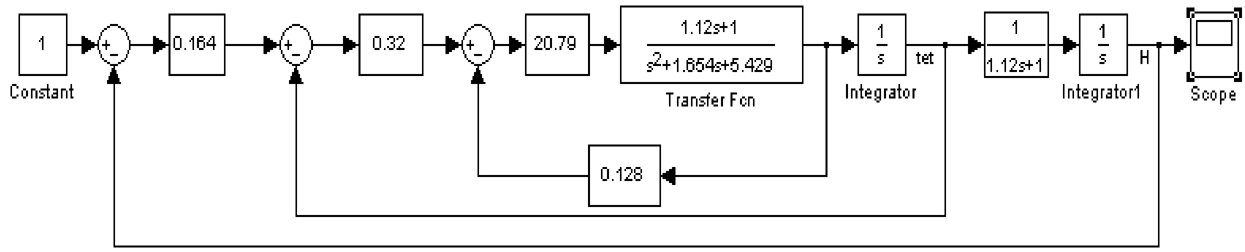

Fig. 5.11 Diagram of the modeling process of the flight height control circuit

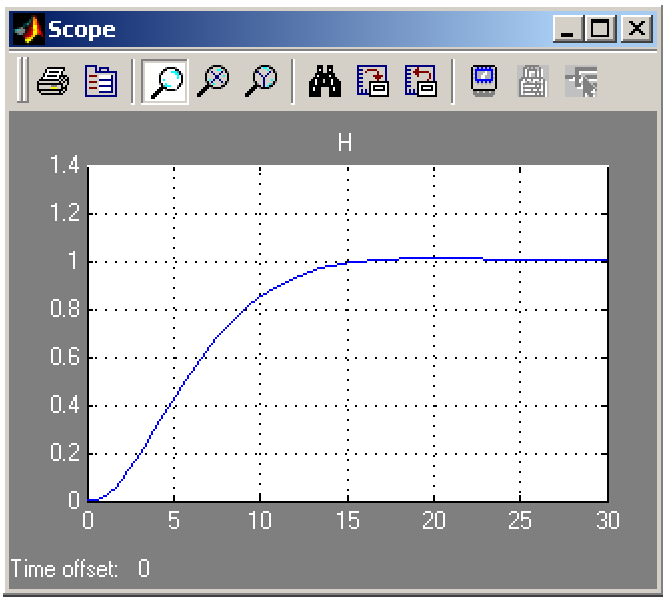

Fig. 5.12 Result of the modeling process of the flight height control circuit

Having modeled the UAV height control circuit, we obtained the results shown in Fig. 5.12. From them, we can see that K_H is calculated correctly.

5.3.5 Research of developed models and algorithms

The simulation of the flight height control algorithm was carried out using the Simulink visual modeling program, which is a component of the MATLAB mathematical programming package.

The structure of the UAV mathematical model is presented in Fig. 5.13.

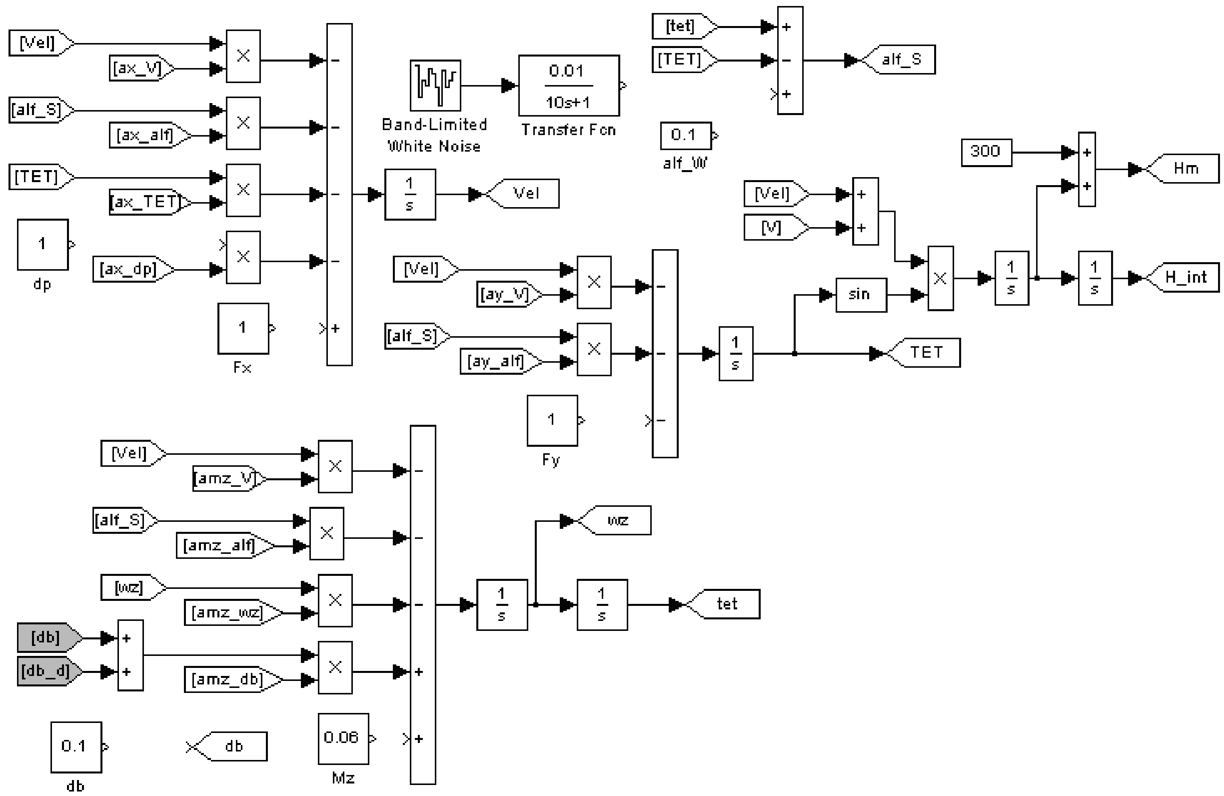

Fig. 5.13 Structure of the UAV mathematical model

The structure of the autopilot model is shown in Fig. 5.14.

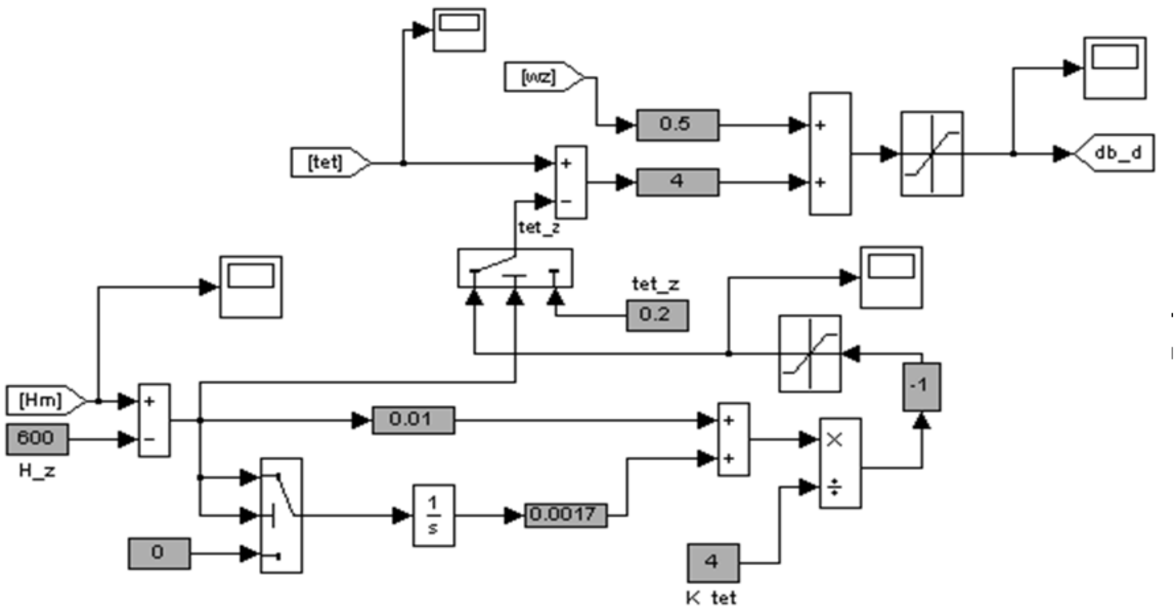

Fig. 5.14 Structure of the autopilot model

During modeling, the following control circuits were studied:

1. The pitch angle control loop during the climb and descent stages, which implements the control law:

$$\delta_{\text{В}} = \text{К}_{\vartheta}(\vartheta - \vartheta_3) + \text{К}_{\omega_Z}\omega_Z$$

At $\vartheta_з \approx 11°$.

The results of modeling the control contours when working out the given pitch angle are shown in fig. 5.15, the change in height is shown in fig. 5.16.

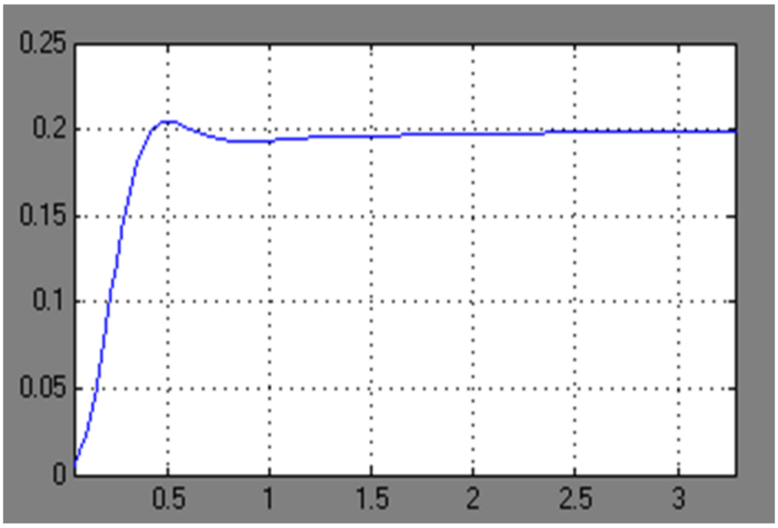

Fig. 5.15 Result of the modeling process with the flight height control loop

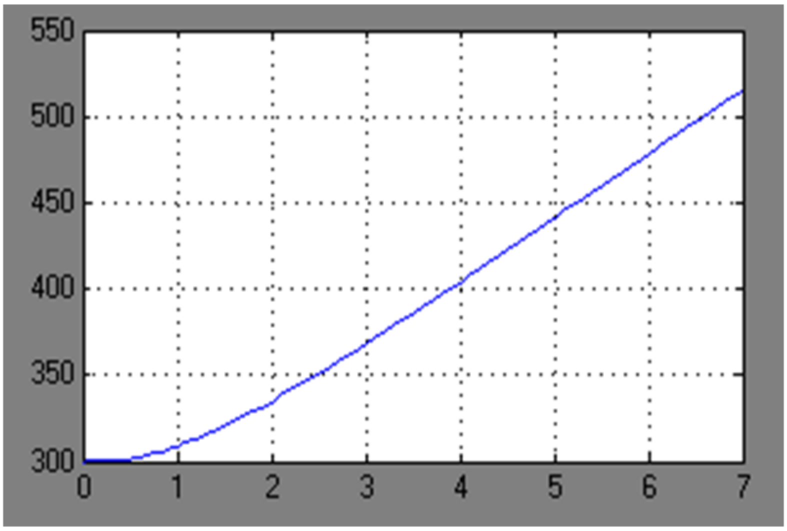

Fig. 5.16 Result of the modeling process with flight height control loop

The control law selected in the work ensures flight even in atmospheric turbulence. At the same time, slight fluctuations in the pitch angle are observed, which is shown in fig. 5.17. Height gain in turbulent mode is shown in Fig. 5.18.

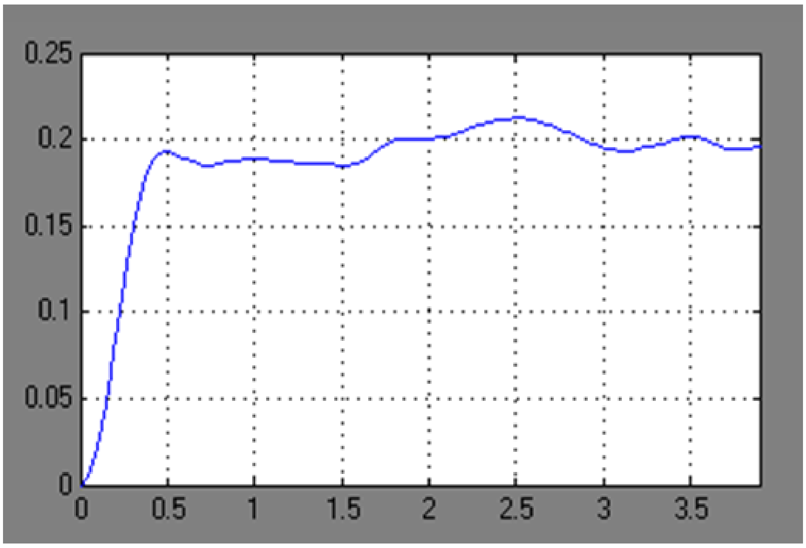

Fig. 5.17 Result of the modeling process with the flight height control loop in "turbulence mode"

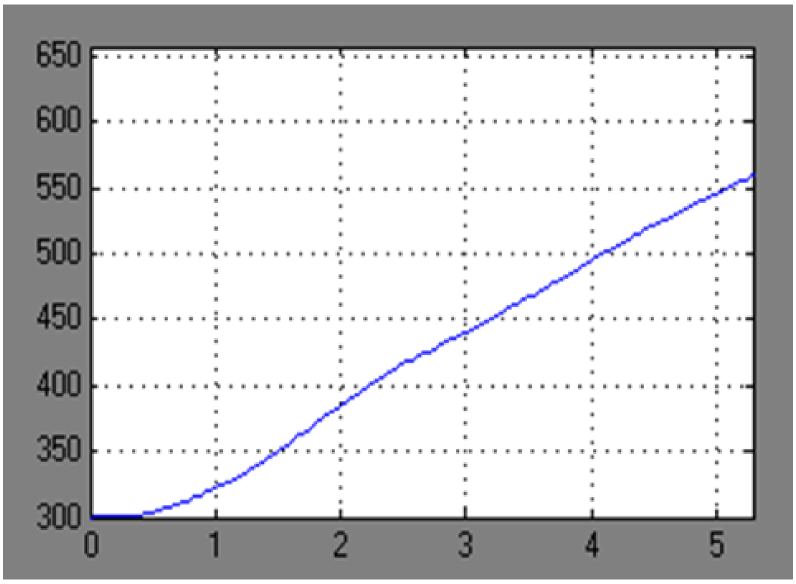

Fig. 5.18 Result of the modeling process with flight height control loop in "turbulence mode"

2. Flight altitude control circuit at the barometric altitude stabilization stage:

$$\delta_{в} = -\frac{1}{К_{\vartheta}}\left(К_{Н} + \frac{К_{\tilde{Н}}}{p}\right)(Н - Н_{з})$$

The results of modeling under the action of a single random disturbance and in the case of atmospheric turbulence are presented in Fig. 5.19 and Fig. 5.20, respectively.

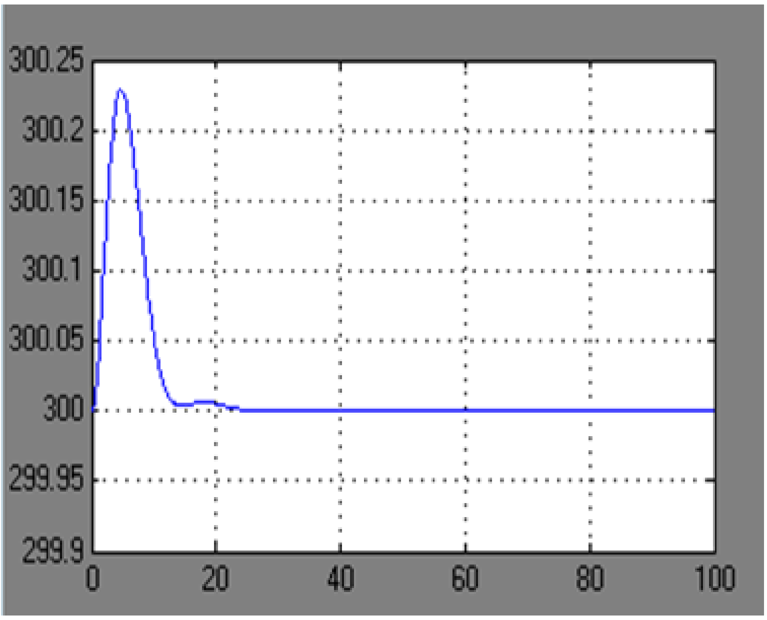

Fig. 5.19 Results of modeling under the action of a single random disturbance at “flight altitude control circuit”

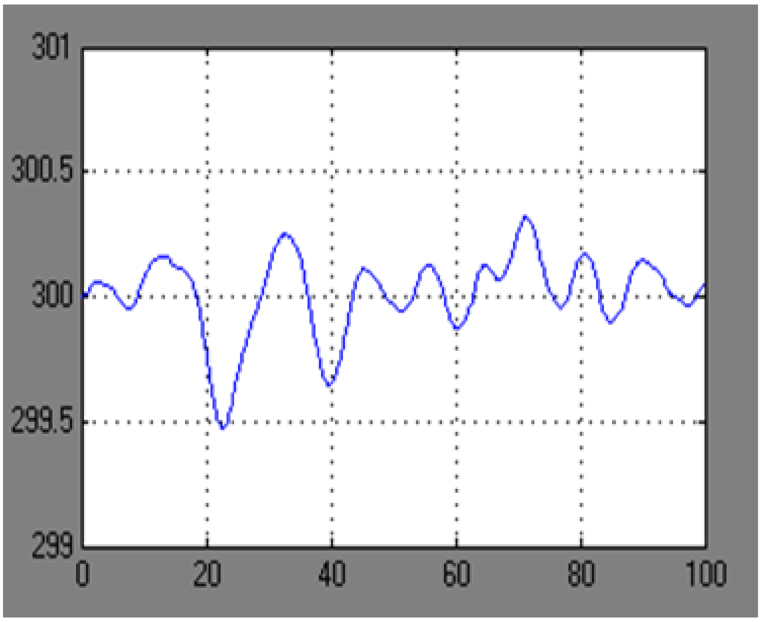

Fig. 5.20 The results of modeling in the case of atmospheric turbulence at "flight altitude control circuit"

The process of UAV transition from one height to another was studied using a mathematical model. It was found that when controlling only the height difference, a significant height overshoot is observed - up to 200m (see Fig. 5.22). When flying according to the developed algorithm, the ascent to a new altitude occurs almost without over-adjustment (see Fig. 5.21), which indicates significant advantages of the transition process.

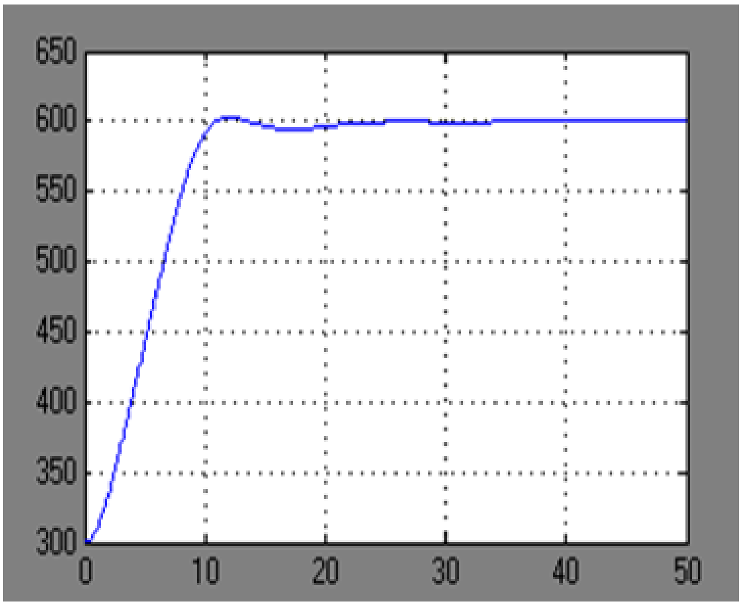

Fig. 5.21 The transition process of the UAV from one altitude to another at flight height control loop

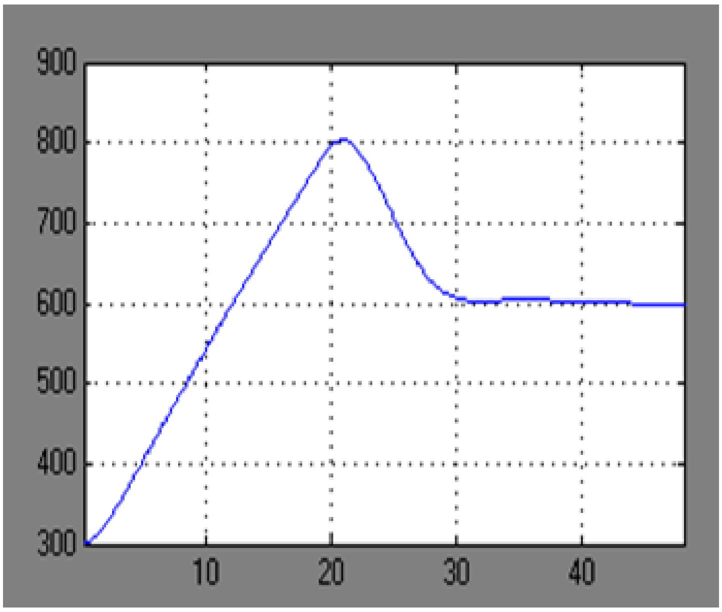

Fig. 5.22 The transition process of the UAV from one altitude to another while controlling only by “flight altitude control circuit”

Thus, the following were investigated: the pitch angle control loop during the climb and descent stages, and flight altitude control circuit at the barometric altitude stabilization stage. Also, an algorithm was developed to combine UAV control loops due to altitude change and pitch angle change, which has good stability and controllability and no large overshoot.

CHAPTER 6. RESEARCH OF THE ISSUE ENVIRONMENTAL PROTECTION USING A UAV

6.1 Current issues of atmospheric air pollution

Atmospheric air pollution [22] is one of the most painful problems of our time. Even a century ago, the composition of the atmosphere, in fact, did not change during the last 300-400 years. However, the rapid growth of industry, the explosive explosion of automobile transport, aviation, the industrial production of petrochemical products, household chemicals, the processing of agricultural land from airplanes, landfills, have led to a progressive increase in atmospheric air pollution, and this trend continues rapidly in the 21st century.

A contradiction arose between comfort, the living conditions of mankind, and how and, most importantly, at the expense of what this comfort and conditions are achieved. Reality is relentless: heat and water in homes, electric current in networks, movement of vehicles of all types and types (cars, airplanes, ships, agricultural machinery), industrial production of almost all goods and products, cooking, the final result is achieved due to the burning of energy resources: firewood, coal, gas, oil products. From the moment when the primitive man in the cave cooked a beefsteak on a bonfire, atmospheric air pollution began. (The history of mankind is essentially the history of obtaining, growing, cooking, storing and consuming meat and other food products). And this contradiction between the benefits of civilization and how these benefits were obtained led to the concept of the "golden billion", when approximately one billion of the world's population enjoys all the benefits of civilization without control and without limit, while the rest survive as they can. The energy equipment of the "golden billion" reaches 25-30 electrical devices per person in the apartment, that is, there are up to 30 devices per person in the apartment (refrigerator, washing machine, TV, stove, coffee grinder, coffee maker, floor heating, electric shaver, electric kettle, electric meat grinder, kitchen harvester, iron, printer, computer, sound speakers, electric heater, air conditioner, freezer, vacuum cleaner, fan, mixer, hair dryer, electric tools, various chargers, etc.) and which must be constantly or periodically plugged into an electrical outlet, and this ultimately leads to atmospheric pollution, because electricity is produced in the process of burning energy resources.

One of the main sources of atmospheric pollution is road transport. Car emissions contain such harmful substances as carbon monoxide, nitrogen oxides, solid particles and volatile organic compounds. 90% of carbon dioxide emissions that enter the atmosphere are caused by road transport. In the case of its high content in the air, the gas causes drowsiness and even leads to death. The maximum number of emissions is recorded during peak hours, and the concentration of harmful substances inside the car is the highest. It is assumed that nitrogen dioxide irritates the lungs and causes an exacerbation of asthma.

Solid particles that settle around (including on our clothes and skin) are a component of pollution from vehicles. The smallest of them (with a diameter of up to 10 micrometers, that is, one hundredth of a millimeter) can penetrate deep into the lungs, exacerbating respiratory diseases. A significant amount of these particles are emitted into the air by cars with diesel engines and large trucks.

Exhaust gases contribute to the formation of the greenhouse effect, which causes global warming. Volatile organic substances, such as polyaromatic hydrocarbons and benzene, lead to the formation of smog. Hydrocarbon emissions are the result of incomplete fuel combustion. These can be gases or solid particles. Benzene (which enters the atmosphere with exhaust and fumes from gas tanks and gas stations when cars are refueled) can cause lung cancer and respiratory diseases.

Each car, when burning 1 kg of gasoline, uses 15 kg of air, in particular, 5.5 kg of oxygen. During combustion, 1 ton of fuel is released into the atmosphere

200 kg of carbon monoxide. Motor vehicles account for about 55% of total harmful inputs, which include more than 200 different compounds, including: carbon, lead, nitrogen oxides, formaldehydes, in particular aromatic hydrocarbon impurities, benzo(a)pyrene, carcinogens, including surfactants , including many mutagens. It is possible to solve this problem through the production and introduction of new (alternative) types of environmentally safe fuel, for example, hydrogen.

Photochemical smog (a nebula of caustic gases visible to the naked eye, characteristic of large cities) is formed as a result of the action of solar ultraviolet radiation on hydrocarbons and nitrogen oxides. Due to temperature inversions, smog hangs over the city and does not dissipate.

Motor transport is not the only cause of air pollution. Its main source is industrial enterprises. Combustion, for example, of coal at thermal power stations is accompanied by emissions of smoke, which contains sulfur dioxide and nitrogen oxide. In addition to the effects mentioned above, sulfur dioxide can cause narrowing of the respiratory tract and aggravate various diseases. During the production of plastics, chlorofluorocarbon will enter the atmosphere, which destroys its ozone layer. Distinguished by high stability, these gases are able to accumulate and remain in the atmosphere for up to 100 years.

When burning a large amount of household waste, smoke containing dioxins is produced. These substances contain perchlorethylene, which was included by specialists in the list of "air pollutants harmful to health" that have carcinogenic properties.

In order to reduce emissions into the atmosphere, systems for controlling emissions of combustion products are constantly being installed in developed countries. Control over the content of exhaust gases is being strengthened, and a fine is imposed for exceeding the norms. Gives results and installation of treatment facilities at power plants and other industrial enterprises. The introduction of flue gas desulfurization technology at coal-fired thermal power plants allows to significantly reduce the content of sulfur dioxide in the smoke. The combined use of heat and energy in industrial enterprises means that the heat, instead of "going to the wind" and dissipating in the atmosphere, will heat the premises.

Installation of catalytic converters on gasoline car engines will allow to reduce emissions of nitrogen oxides, carbon monoxide and hydrocarbons into the atmosphere by more than 75%.

To solve the problem, it is necessary to implement:

- the use of special motor oils, additives to them and fuel, modifiers of car kinematic units, introduction of catalytic fuel converters, etc. on motor vehicles, which will lead to a decrease in fuel consumption, a decrease in emissions of pollutants and an increase in the motor resources of engines;

- strict control over the quality of fuel supplied and sold by gas stations, its compliance with state standards.

The analysis of the current situation of bringing domestic environmental protection practices in line with the standards of the European Union confirms that the complexity of the problem and the lack of established mechanisms for regulating the ecological state of atmospheric air, which would ensure its predicted quality and compliance with environmental standards, creates obstacles to the prospect of harmonization of environmental legislation, and establishes non-compliance with the requirements of European environmental law.

Currently, there is an urgent need to develop stricter standards for emissions of pollutants into the atmosphere by stationary sources of emissions, as well as the introduction of annual monitoring of toxic emissions from mobile sources.

6.2 Main atmospheric air pollutants: characteristics, effects on the human body

The main pollutants of the atmosphere [23] are products of combustion into heat — power plants: boiler houses, thermal power plants, thermal power plants, various furnaces: in metallurgy, oil refining, production of building materials, chemical compounds, etc. and of course lastly: vehicles.

Almost all thermal power plants and transport emissions contain a "gentleman's set" of the main carcinogenic pollutants that arise during combustion:

Particulate Matter (PM), ozone (O_3), carbon monoxide (CO), sulfur dioxide (SO_2), nitrogen oxides (NO_x), volatile organic compounds (VOC), heavy metals.

The main characteristics of these pollutants are as follows:

1. **Solid particles** or Particulate Matter (PM) — fine dust, which consists of the smallest solid and liquid particles, which are divided into groups depending on fractions. Particles with a diameter of up to 10 microns (PM10) are called particulate matter. These particles, 3 to 10 microns in size, settle in the nose and larynx. Particles with a size of about 2.5 microns (PM2.5) enter the lungs when inhaled. Particles smaller than 1 μm (PM1) enter the alveoli and further into the circulatory system.

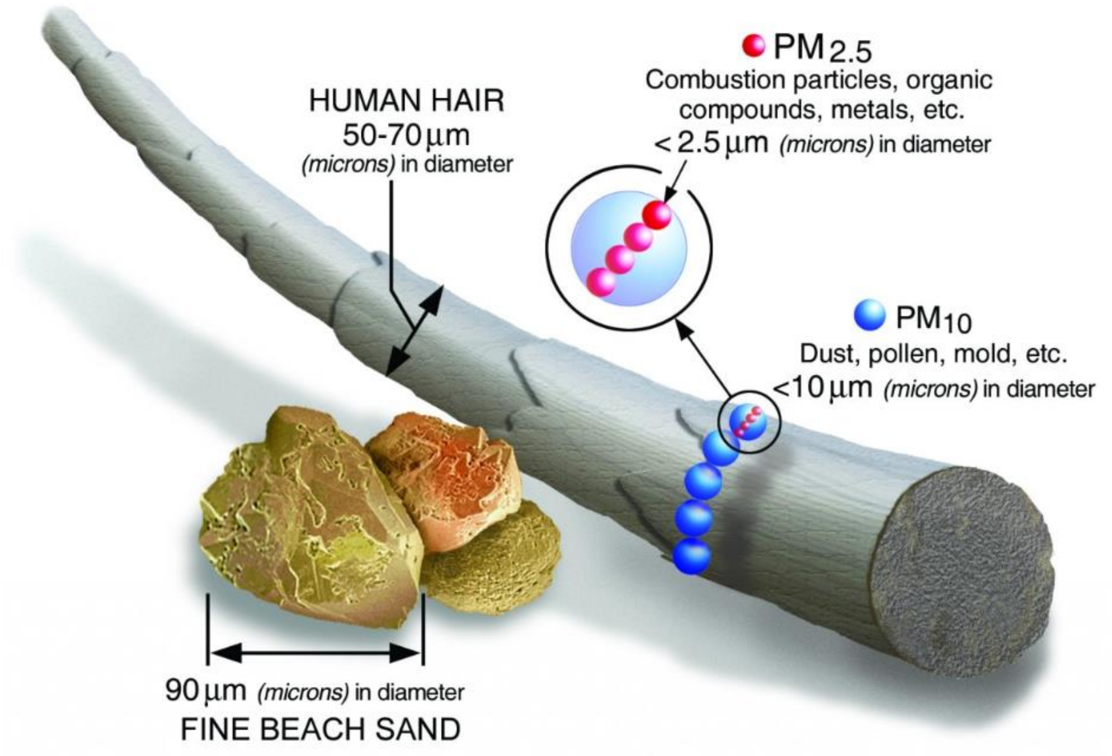

Fig. 6.1 Size comparisons for PM particles

In a simplified concept, PM is dust and the components of PM are sulfate, nitrate, ammonia, sodium chloride, soot, mineral dust, water. Particulate matter consists of a complex mixture of solid and liquid particles of organic and inorganic materials that are ("floating") in the air. The most common damaging particles are particles 10 microns or smaller, which can penetrate and travel deep into the lungs. There is a strong relationship between exposure to small particles (≤ 10 µm) and increased mortality and pain, either daily or intermittently. Conversely, as the concentration of fine and fine particles decreases, the mortality rate also decreases. Small pollutants affect health even at very low concentrations. In developing countries, exposure to indoor pollutants from traditional heating stoves can increase the risk of acute respiratory infections and death in young children. Air pollution from solid fuel use is also a major risk factor for cardiovascular disease, chronic obstructive pulmonary disease, and lung cancer in adults.

It was the significant amount of PM in the emissions of diesel engines of cars that led to the actual prohibition of their use in passenger cars in the countries of Western Europe and America, but large trucks still remained, as well as construction, road and agricultural machinery, which are a source of emissions of solid particles.

Scientists have conducted research according to which up to 15 kg of rubber dust enters the air from a passenger car with four wheels, up to the stage of "bald tire" during operation, and up to 80.0 kg from large vans, buses, trolleybuses. Carcinogenic road marking paint is applied to the road almost every year by millions of tons, and then everything turns into PM and enters our lungs.

2. **Ozone (O_3):**

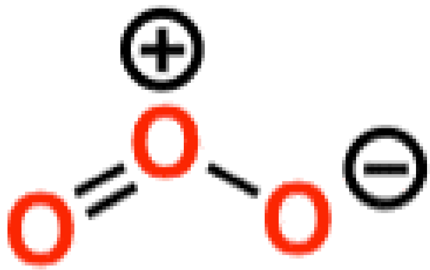

Fig. 6.2 Ozone (O_3)

Ground-level ozone is one of the main elements of photochemical smog. Ozone is formed in the atmosphere and by the reaction of sunlight (photochemical reactions) with pollutants such as nitrogen oxides (NOx) from vehicles and industry, emitted by vehicles, solvents and industry. As a result, the highest levels of ozone pollution occur during periods of sunny weather. Excess ozone in the air significantly affects human health. It can cause breathing problems, trigger asthma, reduce lung function, and cause lung disease. Currently, ozone is considered the most unfavorable air pollutant in Europe. Several studies in Europe reported a 0.3% increase in daily mortality and a 0.4%

increase in heart disease with every 10 microgram per cubic meter increase in ozone in the air.

In many European countries, stationary ozone gas analyzers are installed at the entrance to pharmacies and medical institutions, which display the ozone concentration on a digital display and recommendations for different segments of the population (children, pregnant women, pensioners, etc.) about the period of stay in such "ozonized" air.

3. **Nitrogen dioxide (NO_2) and nitric oxide (NO):**

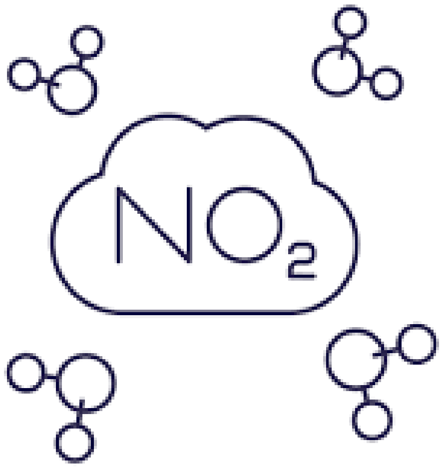

Fig. 6.3 **Nitrogen dioxide** NO_2

At short-term concentrations exceeding 200 micrograms per cubic meter, nitrogen dioxide is considered a toxic gas that causes significant inflammation of the respiratory tract. NO_2 is the main source of nitrate aerosols, which form small particle fractions. The main source of NO_2 emissions is the combustion process (heating, electricity production, vehicles and ships). Epidemiological studies show that bronchitis symptoms in children with asthma increase after long-term exposure to NO_2. Decreased lung function is also associated with NO_2. During the interaction of nitrogen oxides with water vapor (with significant atmospheric humidity), vapors of nitric and nitrous acids are formed, which destroy human lungs and have a significant negative impact on flora and fauna. When burned in power plants, it forms the so-called "red fox tail" from the chimney.

4. **Sulfur dioxide (SO_2):**

Sulfur dioxide is a colorless gas with a pungent odor. It is formed by burning fossil fuels (coal and oil) and processing mineral ore containing sulfur. (When burning gas, sulfur dioxide is not formed). Significant amounts of SO_2 are produced during the burning of sulphurous fossil fuels (coal, firewood, pellets) for domestic heating, electricity production (coal-fired thermal power plants, thermal power plants) and motor vehicles (diesel). SO_2 can affect the respiratory system and lungs and cause eye irritation. Inflammation of the airways that causes coughing, mucus production, asthma, chronic bronchitis and makes people more susceptible to respiratory infections. Hospitalizations due to illness and death from heart problems continue to increase when SO_2 levels are high.

At a concentration of 0.04-0.5 mg/m3, a threat to life is created within a few minutes. Concentrations of 1400 mg/m3 for 5 minutes and 7800 mg/m3 for 30 minutes are considered lethal. Vapors lead to convulsions, loss of consciousness and death from cardiac arrest and paralysis.

5. **Carbon monoxide** (or carbon dioxide) – (CO).

This gas prevents the blood from absorbing oxygen. This can cause a significant decrease in the oxygen supply to the heart, especially in people with heart disease. CO combines with hemoglobin 250 times easier than oxygen - carboxyhemoglobin is formed (HbCO), which cannot transport oxygen, resulting in hypoxia, formation of free radicals and damage to cell membrane structures. Carbon monoxide is present everywhere during the burning of any type of fuel: fossil, mineral, gas, etc. It is a kind of "universal soldier" of pollution: coal-fired thermal power plants, thermal power plants, boiler houses, metallurgy, oil refining, home furnaces, fireplaces. vehicles are sources of carbon monoxide emissions.

As an example, when 1 kg of fuel is burned in a gasoline internal combustion engine in a mid-range passenger car, up to 460 g of carbon monoxide is produced. Therefore, first of all, it is carbon monoxide that must be neutralized by neutralizers and catalysts of modern cars.

Tables 1 and 2 show the current sanitary and hygienic standards for the pollutants discussed above, both in the air of the working area and in the ambient air, which operate in Ukraine since 2020.

Table 1. Sanitary and hygienic standards for the above-mentioned pollutants in the air of the working area (that is, in the workplace of the employee)

Name	Maximum permissible concentration (MPC)	Danger class
Carbon dust	4,0-10,0	3
Ozone	0,1	1
Nitrogen dioxide	2,0	3
Nitrous oxide	5,0	3
Sulfur dioxide (Sulfuric anhydride)	10,0	2
Carbon oxide	20	4

Table 2 Hygienic standards for the content of chemical substances in atmospheric air

Name	Maximum permissible concentration (MPC) mg/m^3		Danger class
	maximum one time	average daily	
Different dust	0,15, -0,5	0.0001-0,15	3
Ozone	0,16	0,03	1
Nitrogen dioxide	0,2	0,04	3
Nitrous oxide	0,4	0,06	3
Sulfur dioxide (Sulfuric anhydride)	0,5	0,05	3
Carbon oxide	5,0	3,0	4

Thus, it is now extremely necessary to study the Earth's atmosphere in order to objectively assess the composition of the air, and accordingly reduce the amount of hazardous substances in the air.

6.3 Environmental monitoring systems

Environmental monitoring [24] - comprehensive observation of the state of the environment, including the components of the natural environment, the natural ecosystem, phenomena and assessment of forecasting of environmental changes.

When organizing monitoring, it is necessary to solve several issues at different levels, therefore, three stages (types, directions) of monitoring can be distinguished: bioecological (hygiene and sanitation), geosystemic (natural and economic) and biospheric (global). However, this method does not clearly separate the functions of its subsystems in terms of environmental monitoring, neither units nor parameterized organizations, and it is mainly of historical significance.

The main tasks of environmental monitoring are: monitoring the state of the environment, assessing and forecasting its state, determining the degree of influence of human factors on the environment and sources of influence. The environmental monitoring system is based on the following principles: objectivity and reliability;

• Systematic monitoring of environmental conditions;

• Consistency of supervision and support methods;

• Consistency of hardware and software;

• Comprehensive assessment of information;

• Effectiveness of information transfer between independent links of the system;

• Open information for the public.

6.3.1 Classification of environmental monitoring process

According to the spatial principles, there are: point, local, regional, national and global observation. The latter includes ecological studies of the interaction of man and nature in the entire biosphere. As a rule, national is carried out within one state. It is very difficult to clearly define the scope of regional monitoring. There are also large observation areas in interstate waters and territories (Baltic Sea, North Sea, Alps, etc.). Local observation includes the study of one space under the influence of a group of companies of an industrial zone, municipal education (city, region).

According to the conditions, the following types of monitoring [25] can be distinguished:

Bioecological (sanitary and hygienic) monitoring aims to monitor the state of the environment and its impact on human health to protect the environment from negative factors;

Geoecological monitoring consists in observing changes in natural ecosystems and their transformation, as well as modeling and forecasting natural changes in the environment that degrade the habitat;

Monitoring of the geological environment - monitoring of rocks;

Biosphere (global) monitoring is the monitoring of natural processes and phenomena at the level of the biosphere, as well as by elucidating global changes in natural background indicators;

Geophysical monitoring is a system of observing natural and artificial geophysical fields and phenomena, as well as observation, analysis and forecasting of environmental pollution caused by hazardous substances;

Climate monitoring is observation of the state of the climate system (atmosphere-ocean-lithosphere-cryosphere-biota), as well as assessment and forecasting of likely climate changes;

Biological monitoring is the control of the state of the environment with the help of organisms;

Satellite observation uses the method of remote control and allows monitoring the changes occurring on the earth's surface and atmosphere using space images. In addition, depending on the purpose, routine, crisis and background monitoring can also be carried out:

Conventional (standard) environmental monitoring is a combination of the optimal number of parameters, observations at these points, which makes it possible to make management decisions at various levels based on the assessment and forecast of environmental conditions.

Operational (crisis) ecological monitoring is an in-depth observation of natural objects that have harmful ecological consequences caused by accidents and natural phenomena in areas with high ecological pressure. In order to respond to emergency situations and take measures to eliminate these problems, there is constant monitoring of these territories to create normal conditions for the life and management of the population.

Background (scientific) ecological monitoring is a particularly high-precision observation of all components of the environment and the nature, composition, circulation and migration of pollutants, individual populations, ecosystems and even the reaction of organisms to pollution at the level of individual populations, ecosystems and the entire biosphere.

In nature reserves and biosphere reserves, background monitoring is carried out at the base station.

6.3.2 Environmental monitoring levels

Monitoring is a multi-level system [26]. Systems (or subsystems) are usually distinguished at detailed, local, regional, national and global levels.

The lower level is the level of detailed monitoring carried out on small areas. When combining detailed monitoring systems into a larger network (for example, within the district, etc.), a monitoring system is formed at the local level. Local supervision is designed to evaluate changes in the system in a larger area (city, district). Local systems can be combined into larger systems - regional surveillance systems covering territories within the region or several at once. This regional monitoring system integrates data from the surveillance network, which differ in methods, parameters, monitoring area and frequency, thanks to which it is possible to fully form a comprehensive assessment of the territorial situation and forecast its development.

A regional surveillance system can be integrated into a single state surveillance network within the state to form a national level. Within the framework of the UN environmental plan, the task is to integrate the national monitoring system into the intergovernmental network, the Global Environmental Monitoring System (GEMS). This is the highest level of environmental monitoring in the world. Its purpose is to monitor changes in the Earth's environment and common resources on a global scale. Global monitoring is a system that monitors the state and predicts possible changes in global processes and phenomena, including technogenic impact on the entire Earth's biosphere. For now, since many countries do not yet have their national systems, the task for the future is to create such a system under the auspices of the United Nations.

The global environment and resource monitoring system is aimed at solving the global environmental problems of the planet, such as global warming, protection of the ozone layer, earthquake prediction, forest protection, global desertification and soil erosion, floods, food and energy supply, etc. An example of such a subsystem of environmental monitoring is the Global Earthquake Monitoring Network, which operates within the framework of the International Earthquake Monitoring Program.

6.3.3 Assessment of the environment state

Assessment of the state of the environment - comparison of the parameters obtained as a result of monitoring activities with the established standards in order to determine the quality of the environment or its individual components.

Environmental quality is the state of natural and altered ecosystems, their ability to maintain their structure and function due to metabolism and energy processes.

Another problem with defining environmental quality is that it cannot be assessed using only one criterion. Therefore, environmental quality indicators are used in monitoring practice. Assessment of environmental conditions is based on the concept of environmental quality standardization.

Standardization of environmental quality - setting the nominal parameters of various environmental components, these parameters determine the limits of the maximum possible changes in their composition and characteristics.

The threshold of harmful effects is the smallest amount of exposure (concentration of a substance, strength of physical factors), changes outside this range of exposure exceed the limit of adaptability of living organisms and / or damage ecological stability.

Using the methods of biological testing to determine the value of the threshold effect of one factor on living organisms in laboratory cultures of sensitive organisms, certain standards can be established.

Environmental criteria. Determining the limit of changes in environmental parameters, and exceeding this limit may pose a threat to the stable survival of natural ecosystems.

The problem of establishing ecological standards is that there is a large number of organisms at the same time, and their sensitivity to specific factors varies greatly. In this case, the system formation function of different species is different. Therefore, the ecological criteria (dominant species or the most vulnerable species) for which species should be calculated for environmental quality have not yet been decided.

One of the few factors that can be called "environmental standards" is the MPC. The main purpose of the standard is to maintain the quality of the environment suitable for residential industrial facilities and their fodder bases. In other words, the MPC regulates the negative impact on "useful" populations, which determines an important economic component of the standard.

Recently, various alternative indicators have been proposed. Taking into account regional features, some environmental standards are based on the established standards of the MPC. Some authors have proposed original methods of calculating pollution standards - "ecologically acceptable level" (ECL), ecological MPC, etc. However, these indicators were not generally recognized and were not included in regulatory documents.

Paying attention to the above, it is possible to determine the main directions of research related to: development and improvement of automatic recognition of various objects (taking into account the solution of the simplest problems, including automatic classification of various objects); and ensure reliable radio communication between the UAV and the control point (ground or air); provide UAV attributes so that changes in the environment can be taken into account when performing offline tasks; drones will allow you to perform flight functions, or choose an alternative route and interact with checkpoints. Therefore, the main advantage of using an unmanned aerial vehicle during environmental monitoring is that it can be observed by receiving data from a remote device, and flight control along the trajectory can be carried out due to the interaction of the UAV with the GPS system. In addition, the ability to use unmanned aerial vehicles also provides observational data on environmental objects and terrain, environmental conditions, and the ability to visualize and evaluate observation areas in real time. The widespread use of unmanned aerial vehicles in environmental monitoring is associated with the development of various equipment and equipment for environmental assessment, which makes it possible to use them to expand the scope of monitoring tasks. Therefore, an important factor in determining the ability to monitor and assess the environment is the choice of drones and aerial systems to solve the tasks of regional environmental monitoring.

In this case, performance monitoring and control are performed on the basis of telemetry information. As a rule, the UAV is equipped with a GPS receiver that determines the coordinates, thereby ensuring a certain degree of coordinated flight and stability of the aircraft. The above two UAV control methods belong to the remote-control type. This type of UAV is called a remote-control aircraft (UAV).

Automatic control of the UAV provides the ability to fly autonomously along a given trajectory with a given speed and angle of orientation. Automatic control performed by a full-fledged UAV autopilot ensures that the aircraft can fly safely in almost any weather conditions, without the need for communication with a base station. The advantage of this method is the minimal requirements for personnel training and ensuring the safe and efficient operation of unmanned aerial systems.

6.3.4 Areas of use of UAVs for environmental monitoring

1) Spectral photography. A type of photography with obtaining in the process of photographing the image of objects in different zones of the spectrum. For example, the use of drones in agriculture allows obtaining terrain models with a resolution of up to 3 cm in the visible and infrared ranges. Due to such a survey, it is possible to fully understand the soil conditions and details, which allows you to control crops with an accuracy of up to 5 cm. The range of data obtained is very wide, problems can be assessed and the causes of various problems can be found.

2) Aerial photography of the area. These are works that include various processes of obtaining photographs of the earth's surface at the expense of flying machines. All materials of aerial photography are used to solve a number of problems of forestry, industry, etc. During the planned shooting process, the camera will be pointed vertically down at right angles to the surface of the ground. In the picture, we see a flat picture (Orthogonal projection), which

resembles an image on a map. During perspective (investigative) shooting, the camera is at a certain angle from the horizontal angle. In this case, we will see a three-dimensional picture (axonometric): not only the roof of buildings, but also the side walls. So we can not only judge the mutual location of objects on the plane, but also related to their shape.

3) Using drones to record animals from the air. The involvement of manned aircraft is not cost-effective, so it is more rational to use UAVs for animal registration equipment. This "aeronautical accounting" allows you to accurately determine the number of animals in the hunting ground and determine where they are concentrated.

4) Remote monitoring of oil and gas pipelines. To date, the use of drones is the most effective and cost-effective method of inspecting oil and gas pipelines. High-quality images are obtained in real time, which can detect oil spills, detect unauthorized activities (landfills, works within protected areas, etc.). Aerial photographs taken with the help of a drone allow to analyze and evaluate technical conditions, the space around pipes and tubules.

5) Space photography of the area. For continuous and simultaneous control of pollution of the natural environment (earth surface, water and surface atmosphere), to monitor the technical condition of objects with a length of thousands of kilometers of land, water and land, oil and gas passages. In addition, remote monitoring data helps to quickly identify the exact coordinates of the dangerous zone of natural elements, processes that can lead to an accident, as well as to track and predict problems.

6) Geodetic survey. The type of monitoring that can be used in the following areas of activity:

• Maintenance of the national real estate cadastre and settlement control of urban planning activities;

• Response to emergency situations;

• Control of ice and snow cover, the edge of the ice sheet, monitoring of floodplains;

• Update of topographic maps;

• Control of various types of objects;

• Monitoring of the state of agricultural land, including target indicators, assessment of land use, state and degree of land degradation, production forecast;

• Creation of geographic information systems.

7) Monitoring and detection of moving objects. Supervision in the guarded area day and night.

8) Monitoring of forest resources. Including assessment of the degree of deforestation, identification of tree types, detection of forest fires (dry forests, smoldering peatlands, detection of small fire sources), assessment of damage to forest resources after fires, natural disasters, and detection of unauthorized landfills.

Determining the number of violators and identifying their means of transportation. A drone's infrared camera can be used for early detection of forest fires.

9) Supervise repair and construction works:

Compared to traditional methods, this method can significantly speed up work and reduce labor costs. This allows you to assess the facility's readiness; identify and analyze damage, accidents; plan maintenance work; to simulate natural influence.

10) UAVs in the security field:

Increase security by controlling certain objects and people in the area. Most of the time ordinary guards spend on patrolling, while drones do it many times faster. There are many examples: in order to avoid unauthorized intrusion, the UAV patrols oil and gas pipelines, areas with natural resources, urban and intercity transport routes, power lines, routes during important events.

11) Unmanned border guard. Surveillance abroad using infrared and conventional cameras. The height can be up to 6 kilometers with the possibility of observation up to 50 kilometers. From the video camera, it is clear enough that the criminal can be seen in detail from a height.

After all the above analysis, we can conclude: in the near future, drones will take the top place compared to manned ones, this can be explained by the following facts: UAVs do not require human resources, so no one will put their lives in danger, so the drone is very safe, and has wide application in security and defense industry, and environmental monitoring. The priority directions of this market are considered to be fast communication. Remote sensing and surveillance, search and rescue, agriculture and transport. UAVs in these systems are in great demand and have wide prospects in the market.

By studying dangerous areas and receiving information about the level of pollution, the ground system reacts more slowly in emergency situations.

The method of using UAVs in environmental monitoring is divided into several stages:

• tasks of environmental monitoring;

• selection of technical means for monitoring the environment (determine the capabilities of measuring equipment, determine the number of drones used, determine the best route for research);

• selection of technical means of environmental data collection;

• measurement of environmental parameters;

• processing of environmental parameters;

• comparison of ecological parameters with ecological standards;

• analysis of environmental parameters;

• forecasting the state of the environment in the future.

6.4 Research of Geographical Information Systems for environmental protection

All over the world, the problems of environmental protection are now receiving increased attention. And it is not surprising. The rapid development of people's economic activity has created all the prerequisites for the real possibility of an ecological crisis. In this connection, the direction related to the quantitative assessment of anthropogenic impacts on the environment, the creation of systems for comprehensive assessment of the state of the ecological situation, and modeling and forecasting of the development of the situation is gaining great importance. The creation of such systems is currently impossible without the use of modern computer tools. GIS technologies [27] are one of the important tools.

Assessment of the state of complex natural objects in the environment implies a comprehensive analysis of the influence of various factors. Obtaining comprehensive assessments is complicated by the variety of object characteristics, the variety of available information, which increases the urgency of the task of ensuring metrological comparability of disparate data.

6.4.1 Analysis of habitat degradation

GIS is successfully used to create maps of the main parameters of the environment. In the future, upon receiving new data, these maps are used to identify the scale and rates of degradation of flora and fauna. When entering data from remote, in particular satellite, and regular field observations, they can be used to monitor local and large-scale anthropogenic impacts. Data on anthropogenic loads should be superimposed on the zoning maps of the territory with selected areas that are of special interest from the point of view of nature conservation, for example, parks, nature reserves and nature reserves. Assessment of the state and rates of degradation of the natural environment can also be carried out on the test areas selected on all layers of the map.

6.4.2 Study of contaminated areas

With the help of GIS, it is convenient to model the impact and spread of pollution from point and non-point (spatial) sources on the terrain, in the atmosphere and along the hydrological network. The results of model calculations can be superimposed on natural maps, such as vegetation maps, or on maps of residential areas in a given area. As a result, it is possible to quickly assess the immediate and future consequences of such extreme situations as oil spills and other harmful substances, as well as the impact of persistent point and plane pollutants.

6.4.3 Study of reserved areas

Another common area of application of GIS is the collection and management of data from protected areas, such as sanctuaries, nature reserves, and national parks. Within the protected areas, it is possible to carry out full spatial monitoring of plant communities of valuable and rare animal species, to determine the impact of anthropogenic interventions, such as tourism, road construction or power lines, to plan and implement environmental protection measures. It is also possible to perform multi-user tasks, such as regulating livestock grazing and predicting land productivity. GIS solves such tasks on a scientific basis, that is, solutions are chosen that ensure the minimum level of impact on wildlife, maintaining the required level of cleanliness of air, water bodies and soils, especially in areas frequently visited by tourists.

6.4.4 Research of protected areas

Regional and local governing structures widely use GIS capabilities to obtain optimal solutions to problems related to the distribution and controlled use of land resources, settlement of conflict situations between land owners and tenants. It is useful and often necessary to compare the current boundaries of land use plots with land zoning and prospective plans for their use. GIS also provides the ability to compare land use boundaries with wildlife requirements.

For example, in a number of cases it is necessary to reserve the migration corridors of wild animals due to the development of the territory between nature reserves or national parks. Constant collection and updating of data on land use boundaries can provide great assistance in the development of environmental protection measures, including administrative and legislative measures, monitor their implementation, make timely changes and additions to existing laws and regulations based on basic scientific ecological principles and concepts.

6.4.5 Habitat restoration analysis

GIS is an effective tool for studying the habitat as a whole, individual species of flora and fauna in spatial and temporal aspects. If the specific parameters of the environment, necessary, for example, for the existence of any kind of animal, including the presence of pastures and places for breeding, appropriate types and stocks of fodder resources, water sources, requirements for the cleanliness of the natural environment, are established, then GIS will help to quickly find areas with a suitable combination of parameters, within which the conditions for the existence or restoration of the population of this species will be close to optimal. At the stage of adaptation of the resettled species to the new area, GIS is effective for monitoring the immediate and distant consequences of the measures taken, evaluating their success, identifying problems and finding ways to overcome them.

6.4.6 Study of the monitoring process

As nature protection measures expand and deepen, one of the main areas of GIS application is monitoring the consequences of actions taken at the local and regional levels. The sources of updated information can be the results of ground surveys or remote observations from air transport and from space. The use of GIS is also effective for monitoring the living conditions of local and introduced species, identifying cause-and-effect chains and relationships, assessing the favorable and unfavorable consequences of environmental protection measures taken on the ecosystem as a whole and its individual components, making operational decisions regarding their adjustment depending on changing external conditions.

So, GIS technologies are not just a computer database. These are huge opportunities for analysis, planning and regular updating of information. Today, GIS technologies are used in almost all areas of life, and it helps to solve many tasks really effectively. In particular, the tasks are related to environmental safety in the urban environment.

CHAPTER 7. LABOR PROTECTION

7.1 Dangerous and harmful occupational safety factors for unmanned aerial vehicles

The thesis examines the process of creating a digital system of automatic control of an unmanned aerial vehicle. An unmanned aircraft is an aircraft that flies and lands without the physical presence of a pilot on board. That is why the automatic control system should be created in such a way that a person hardly comes into contact with the UAV.

The UAV automatic control system, which is considered in the thesis, ensures the correctness and smoothness of the movement of the UAV depending on its control using an electric remote control [28]. To ensure proper operation of the electrical equipment of this system, personnel must follow all electrical and safety instructions.

In order to avoid injuries, malfunctions, emergency situations, occupational diseases and equipment failure, a person who is engaged in adjustment, integration and repair must follow clear instructions. Individuals at least 18 years of age who have passed a medical examination and have no medical contraindications, who have undergone special training, certification and have a relevant certificate, who have undergone introductory training on labor protection, training at the workplace and training on fire safety, are allowed to independently service electrical installations. Employees who maintain electrical installations are required to have an appropriate electrical safety group. Know and be able to apply safety rules in practice to the extent necessary for the work being performed.

When setting up, testing and debugging electrical equipment, it is necessary to strictly follow the Rules for the operation of electrical equipment, it is necessary to strictly follow the Rules for the operation of electrical equipment, the Rules for safety during the operation of consumer electrical equipment and technological processes.

When working with electrical equipment, there are many dangerous and harmful factors for the personnel who maintain it. Some of them:

– electric shock;

– falling during work at height;

– increased air mobility;

– increased level of static voltage;

– burns during the performance of power cable repair work (heating of the cable mass);

– injury by rotating parts of electric drives, parts of machines and mechanisms;

– electric arc burns during short circuits;

– electric field strength is more than 5 kW/m;

– step and applied voltage;

– increase or decrease in ambient temperature;

– traffic in the working area, during the location of substations and substations next to roads and other transport highways;

– insufficient lighting of the working area;

– action of chemicals (acetone);

– insufficient illumination of the working area.

Parts of tools that are isolated and used for servicing electrical equipment must be made of conductive materials.

When working in an explosive zone, the use of materials or tools that can cause sparks is prohibited.

For work in the dark period, for local lighting of the area where work is being carried out, battery lights with a voltage of up to 12 V in an explosion-proof form are used in areas with an increased risk of explosion.

When using absolutely any electrical equipment, it is very important to observe safety rules. Any malfunctions detected in electrical equipment should not be neglected, such a careless attitude, first of all to yourself, leads to injuries of varying degrees of severity, and sometimes to death.

Work safety is greatly influenced by the environment in which electrical installations are operated. Aggressive gases and vapors destroy the insulation of electrical installations, reduce its resistance, and create a threat of voltage transfer to metal structures. This is facilitated by high temperature and air humidity, conductive dust.

In turn, the premises in which electrical equipment is operated are divided into three main categories:

– premises with increased danger;

– particularly dangerous premises;

– premises without increased danger.

Premises with an increased risk of electrocution are characterized by the presence of one of the following conditions:

– humidity (a room in which the relative humidity of the air is more than 60%, but does not exceed 75%);

– conductive dust (technological or other dust settles on the wires, can penetrate inside the machine and devices);

– conductive floors (metal, earth, reinforced concrete, brick); - elevated air temperature (long-term above +35°C, short-term +40°C);

– the possibility of human contact with the metal casings of electrical equipment on the one hand and with the earth-connected metal structures of buildings, technological equipment, and mechanisms on the other.

Particularly dangerous rooms are characterized by the presence of one of the conditions that create a special danger: very high relative humidity (about

100%), chemically active environment; or the simultaneous presence of two or more conditions that create an increased risk.

Premises without increased danger are characterized by the absence of conditions creating increased or special danger (dry administrative premises, etc).

During the analysis of electrotraumatism, four main causes of electric injuries are distinguished, namely: organizational, technical, sanitary-hygienic and psychophysiological. The main causes of electrocution in Ukraine are organizational and technical.

The main organizational reasons are these:

– ineffective supervision - departmental and public control over compliance with safety requirements;

– absence or poor quality of training on labor protection issues;

– absence or untimeliness of conducting medical control of the state of health of electrical personnel;

– violation of the requirements of standards, norms regarding the operation of electrical installations;

– non-implementation of labor protection measures;

– violation of technological regulations;

– violation of regulatory, planned and repair work;

– insufficient technical supervision of dangerous works.

Technical reasons include:

– deviation from general security requirements;

– electrical installation malfunction;

– structural defects of the equipment;

– lack of personal protective equipment;

– lack of signaling devices.

Sanitary and hygienic reasons include:

– increased content of harmful substances;

– insufficient or irrational lighting;

– increased noise level;

– unsatisfactory microclimatic conditions;

– presence of radiation.

Psychophysical reasons include:

– erroneous actions of employees due to fatigue;

– inconsistency of the employee's psychophysiological or anthropometric data with the work performed.

An analysis of industrial injuries shows that a dangerous factor for personnel servicing electrical equipment is electric shock. And the main causes of electrocution are the appearance of voltage in those places where it should not be. The reason for this is a violation of the insulation of cables, wires and windings. The possibility of touching non-insulated parts that conduct current. This happens when the terminals and busbars are placed at an incorrect height. The formation of an electric arc between a conductive part and a person.

Every year in Ukraine, approximately 1,500 people die from electric current. The largest number of cases of electrocution, including those with fatal consequences, occur during the operation of electrical installations with a voltage of up to 1000 V, which is due to their distribution and relative availability for almost everyone who works in production. Cases of electrocution during the operation of electrical installations with a voltage of more than 1000 V are infrequent, which is due to the small distribution of such electrical installations and their maintenance by highly qualified personnel.

The analysis of accidents that are connected with the effect of electric current allows to divide the main causes into groups:

– accidental contact with live parts;

– voltage on metal parts of the equipment;

– mistakenly connecting the equipment under voltage during repair and preventive works on it;

– occurrence of step voltage on the surface of the earth on which a person is located.

Each of the presented groups includes specific dangerous factors, namely:

– violation of the rules of installation, technical operation and safety of electrical installations;

– lack of reliable means of protection;

– imperfection of electrical installation design;

– performing electrical installation and repair works under voltage;

– malfunction of insulation of current-conducting parts of the system;

– mistakenly connecting the equipment under voltage during regular maintenance work;

– low-skilled training by workers who use manual electric machines;

– use of cables and wires that do not meet production conditions.

7.2 Technological measures to reduce the impact of harmful production factors

The development of measures to reduce dangerous factors means the organization of labor protection management [29]. This allows you to reduce the risks of injuries, accidents and deaths, occupational diseases and emergency situations.

Ensuring safety is achieved thanks to the development and implementation of production processes, which are developed in accordance with the requirements of the Order of the Ministry of Social Policy of Ukraine dated 28.12.2017 No. 2072 "Safety and health protection requirements during the use of production equipment by employees", as well as the requirements of state and industry standards of labor safety by types of technological processes and works, norms and rules of state supervision bodies.

The principles of ensuring the safety of activities can be characterized by groups of measures that are performed:

Technical measures — technical means that allow to ensure safe and harmless conditions for the performance of assigned work, introduction of new equipment, devices and appliances. Technical measures can be divided into 2 large groups:

– tools during work on de-energizing existing electrical installations;

– tools during work on conductive parts.

The means of the first group include:

– turning off the installation or part from the power source;

– mechanical blocking of drives that perform shutdown, removal of fuses, disconnection of the ends of the power supply line;

– installation of grounding (turning on grounding knives or installation of portable grounding devices).

The means of the second group include:

– execution of work by order of at least two workers using electrical protective equipment, under constant supervision, ensuring the safe location of workers.

Normative and methodical measures include::

– development of manuals and recommendations;

– development of the regulatory framework;

– development of educational methods;

– development of labor protection sections in job instructions.

Organizational activities include:

– control over the technical condition of the equipment;

– control over compliance with the requirements of regulatory documents on labor protection;

– provision of appropriate safety signs;

– providing employees with means of individual and collective protection.

Sanitary and hygienic measures include:

– provision of sanitary and household conditions in accordance with current regulations;

– control over the influence of production factors on the health of employees;

– planning measures to improve sanitary and hygienic conditions;

– certification of the sanitary and technical state of working conditions.

Socio-economic measures include:

– social insurance of employees by the employer;

– funding of labor protection measures;

– compensation by the employer to the employee in case of mutilation.

Treatment and preventive measures include:

– observance of labor protection of women, minors and disabled persons;

– control over the health of employees during their work;

– provision of medical assistance to victims of industrial accidents;

– conducting medical examinations of employees (preliminary and periodic).

Scientific activities include:

– accident localization and liquidation plans;

– evaluation of the effectiveness of labor protection management;

– simulation of emergency situations and development of measures to prevent them.

The main regulatory documents regarding electrical safety in Ukraine are:

Rules for the installation of electrical installations (RIEI). The RIEI applies to electrical installations under construction or reconstruction with a voltage of up to 500 kV. RIEI establish general requirements for the structure of electrical installations, for sewerage (transmission) of electricity, for protection and automation, for distribution devices and substations, for electric power plants, for electric lighting and for electrical equipment of special installations.

ДНАОП 0.00-1.32–01. Rules for the construction of electrical installations. Electrical equipment of special installations. This document was approved by the Ministry of Labor of Ukraine and includes some issues of electrical lighting and equipment of special installations with changes and additions in accordance with the current Ukrainian and international regulatory acts, namely:

– "Rules for the operation of electric power plants and networks" is a sectoral (energy) normative document, the effect of which applies to electrical installations with a voltage of up to 500 kV, establishing requirements for condition control and maintenance of electrical installations in the energy industry.

– "Rules for the technical operation of electrical installations of consumers" is an inter-branch normative act, the effect of which extends to electrical installations with a voltage of up to 220 kV, establishes requirements for monitoring the condition and maintenance of electrical installations, keeping relevant documentation.

– ДНАОП 1.1.10-1.01-97. Rules for the safe operation of electrical installations – industry normative document (power industry). Its effect extends to electrical installations of the power industry with a voltage of up to 500 kV. It establishes requirements for the safe operation of electrical installations.

– ДНАОП 0.00-1.21-98. The rules for the safe operation of electrical installations of consumers is an interdisciplinary NA that defines the requirements for the safe operation of electrical installations, its effect is extended to electrical installations with a voltage of up to 220 kV.

– ДНАОП 1.1.10-1.07-01. Rules for the operation of electrical protective equipment, which establish requirements for the necessary list of electrical protective equipment depending on specific conditions, for storage, testing, checking the condition and use of electrical protective equipment.

– industry regulations on electrical safety. Inter-branch normative acts on electrical safety do not object to the development of branch NAs if it is expedient. At the same time, sectoral NAs should not interfere with inter-sectoral ones and reduce the level of security.

– normative acts of enterprises on electrical safety issues. Basically, these are instructions for the safe maintenance of electrical installations and the performance of work in electrical installations, developed and approved in accordance with current requirements.

According to the state standards on electrical safety and the Rules for the arrangement of electrical installations, the nomenclature of types of protection against electric shock includes the following means and methods.

Three systems of means and measures for ensuring electrical safety can be distinguished:

– system of technical measures and means;

– system of electrical protective devices;

– a system of organizational and technical measures and means. The main technical means and measures to ensure electrical safety:

– isolation of current-carrying parts;

– protective separation of electrical networks;

– equalization of potentials;

– compensation of capacitive earth fault currents;

– unavailability of current-carrying parts.

Insulation of current parts. Ensures the technical efficiency of electrical installations, reduces the probability of a person falling under voltage, short circuits to the ground and the body of electrical installations, reduces the current through a person when touching non-insulated current-carrying parts in electrical installations powered by an isolated network from the ground, provided there are no phases with damaged insulation.

ДСТУ Б В.2.5-82:2016 "Electrical safety in buildings and structures. In the requirements for protective measures against electric shock" isolation is singled out:

– working — ensures normal operation of electrical installations and protection against electric shock;

– additional — provides protection against electric shock in case of damage to the working insulation;

– double — consists of working and additional;

– reinforced - improved working insulation, which provides the same level of protection as double.

Protective separation of electrical networks. The total resistance of the insulation of the wires of the electrical network relative to the ground and the capacitive component of the ground fault current depend on the length of the network and its branching. As the disorder of the network increases, the capacitance increases and the resistance decreases. Separation of such an extended network into separate, electrically disconnected parts using transformers with a transformation factor equal to unity, 79 contributes to increasing the insulation resistance and reducing the capacity and, as a result, leads to an increase in the level of safety.

Equalization of potentials. It is used for the purpose of reducing the possible contact voltages (U_{con}, B) and (U_{st}, B) of the step during the operation of electrical installations or human exposure to these voltages under other circumstances. During the raising of the potential of the support surface on which a person can be, to the level of the potential of the current-carrying parts that can be touched, potential equalization occurs.

Compensation of the capacitive component of the earth fault current.

The current during single-phase circuits, the current that passes through a person, is estimated by active and capacitive components. Thus, the capacitance of each wire of an overhead network of 6...35 kV is approximately 5000...6000 pF/km, and the capacitive current per 1 kV of line voltage and per 1 km of network length is 2.7...3.3 mA for networks on wooden supports. In networks on metal supports, this current is 15% more. In extensive branched networks, the capacitive component of the current through a person can exceed the active component and be decisive in the severity of electric shock to a person.

System of electrical protective equipment:

ДНАОП 1.1.10-1.07-01 "Rules for the use of electrical protective equipment" (hereinafter the Rules) is a valid regulatory document, which lists protective equipment, requirements for their design, scope and standards of testing, the procedure for use and storage, equipping electrical installations and production crews with protective equipment. The means of protection used in electrical installations must meet the requirements of current state standards, technical conditions regarding their design, etc.

Electrical protection means are divided into insulating (insulating rods, clamps, pads, dielectric gloves, etc.), enclosing (fences, shields, screens, posters) and protective (goggles, helmets, safety belts, gloves for hand protection).

System of organizational and technical measures and means:

The main organizational and technical measures and means for the prevention of electric injuries are regulated ДНАОП 0.00-1.21-98 "Rules for the safe operation of electrical installations of consumers", according to which the responsibility for organizing the safe operation of electrical installations rests with the owner.

According to the law must:

– the main organizational and technical measures and means for the prevention of electric injuries are regulated ДНАОП 0.00-1.21-98 "Rules for the safe operation of electrical installations of consumers", by which responsibility for the organization of safe operation of electrical installations rests with the owner;

– create and staff an electrical service according to needs;

– to create such conditions at the enterprise so that the employees who are responsible for the maintenance of electrical installations, in accordance with the current requirements, carry out their inspection and testing in a timely manner;

– develop and approve job instructions for electrical service workers and instructions for safe performance of work in electrical installations, taking into account their characteristics.

7.2.1 Calculation of contour protective grounding for electrical installation

General electrical safety requirements must be met ДСТУ 7237:2011. Protective grounding is used to protect against electric shock. The purpose of protective grounding is to lower the current that flows through a person (I_p) while touching the grounding body of the diagnostic device when there occurs U_{con} (touch voltage) as a result of damage or insulation breakdown of conductive parts.

The calculation of the circuit in the laboratory is reduced to the determination of the number of vertical grounding devices and the length of the connecting strip.

Grounding is made of tubular vertical grounding rods and is connected by a metal strip. The resistance of the protective ground must satisfy the requirement $R_з \leq 4\ Om$ (for installations with a small earth fault current and voltage up to 1000 V).

Determine the resistance of the ground circuit

1. Under favorable conditions, the resistance of a single grounding device is determined by the formula:

$$R_{rod} = 0.366\frac{p}{l}\left(\lg\frac{2l}{d} + \frac{1}{2}\lg\frac{4H + l}{4H - l}\right) \quad (7.1)$$

where we will choose a rod as a grounding device.

Length: $l = 1.5\ (m)$,

Diameter: $d = 0.016\ (m)$,

The distance from the surface to half the length of the rod: H= 0,85 (м)

Soil resistivity: $p = 102\ Ohm * m$

Substituting the data into formula (6.1), we get the following values:

$$R_{rod} = 0.366\frac{102}{1.5}\left(\lg\frac{2 * 1.5}{0.016} + \frac{1}{2}\lg\frac{4 * 0.85 + 1.5}{4 * 0.85 - 1.5}\right) = 60\ Ohm \quad (7.2)$$

The number of single grounding devices n is calculated using the formula:

$$n = \frac{R_{rod}}{r_{c.g.} * \eta_{rod}} \quad (7.3)$$

Where: $r_{c.g.}$- the value of contour grounding, which normalizes, according to ПУЕ-86.

$r_{c.g.} = 4\ Ohm$;

η_{rod} – utilization ratio of a single grounding rod for rods;

$\eta_{rod} = 0.66$.

According to the following data, we get:

$$n = \frac{R_{rod}}{r_{c.g.} * \eta_{rod}} = \frac{60}{4 * 0.66} = 22\ pcs \quad (7.4)$$

The resistance of the connecting strip connecting single grounding devices:

$$R_{str} = 0.366 \frac{p}{l} \lg 2 * \frac{l^2}{b * H} \qquad (7.5)$$

Where: l – strip length;

$l = a * n = 79.2\ m$;

$a = 3.6\ m$ – the distance between the rods;

$b = 0.04\ m$ –radius;

$H = 0.1\ m$ – the depth of laying the strip;

$$R_{str} = 0.366 \frac{p}{l} \lg \frac{2 * l^2}{b * H} = 0.366 \frac{102}{79.2} lg \frac{2 * 79.2^2}{0.04 * 0.1} = 3\ Ohm \qquad (7.6)$$

The resistance of artificial contour grounding is determined by the formula:

$$R_{c.g.} = \frac{R_{rod} * R_{str}}{R_{rod} * \eta_{str} + n * R_{str} * \eta_{rod}} \qquad (7.7)$$

Where: η_{str} – the coefficient of use of the connecting strip as opposed to the vertical electrodes;

$\eta_{str} = 0.4$.

$$R_{c.g.} = \frac{60 * 3}{60 * 0.4 + 22 * 3 * 0.66} = 2.66\ Ohm \qquad (7.8)$$

The calculated value of the resistance of the grounding circuit does not exceed 4 Ohms, therefore it meets the requirements of electrical safety.

7.3 Measures to ensure safety in the workplace room

To exclude the possibility of electric shock, organizational measures and technical measures are provided.

a) To ensure the ergonomics of the workplace in accordance with the requirements НПАОП 0.00-1.28-10 "Occupational safety rules during the operation of electronic computing machines", where the prohibition of cluttering the workplace, compliance with regulations regarding the workplace area per employee is specified. Also, the requirements for the organization of the workplace are specified in ГОСТ 12.2.032-78 "ССБТ. Workplace when performing work while sitting. General ergonomic requirements".

The design of the workplace, its dimensions and the mutual location of its elements must correspond to the anthropometric, physiological and psychophysiological characteristics of the person, as well as the nature of the work. A workplace arranged in accordance with the requirements of the standards ensures a comfortable position for a person. This is achieved by adjusting the position of the chair, the height and angle of inclination of the footrest, if it is used, or the height and dimensions of the work surface. It is necessary to ensure the performance of labor operations in the zones of the motor field (optimal reach, easy reach and reach) depending on the required accuracy and frequency of actions.

The organization of workplaces should ensure a stable position and freedom of movement of the employee, the safety of labor operations, exclude or allow only in some cases work in uncomfortable positions that lead to increased fatigue.

There should be nothing superfluous in the workplace; all items necessary for work must be near the employee, but not interfere with him. The organization of the workplace should provide the necessary visibility.

b) In order to minimize the negative impact of tension and intensity of work in work, the following are provided: - optimal regime of the labor process; - implement modern methods of psychological relief, which include:

1) use some breaks to perform a set of physical exercises: to reduce neuro-emotional stress, tire the visual analyzer, improve cerebral blood circulation, overcome the adverse effects of hypodynamia, prevent fatigue;

2) when conducting sessions of psychophysiological relief, it is recommended to use some elements of the autogenic training method, which is based on the conscious application of a complex of interconnected techniques of mental self-regulation and the performance of simple physical exercises with verbal self-suggestion. The main attention is paid to the acquisition and consolidation of muscle relaxation skills;

3) breaks are recommended to be spent in a psychophysiological relaxation room with a suitable interior, color design and pleasant soundtrack.

c) To increase labor efficiency, measures are applied to optimize the management of labor organization, which provides:

- system of trainings, training of the management team of the organization, methods of effective management, improvement of organizational culture - a holistic system of behavior models, customs, traditions and expectations developed in the organization and characteristic of its members), ensuring the stability of the team, employee awareness and transparency of the organization's policy.

d) To exclude the possibility of electric shock are provided:

- organizational measures - study and certification of knowledge of electrical safety rules;

- technical measures - arrangement of the grounding system of power-consuming equipment in accordance with the "Rules for the installation of electrical installations" "(RIEI)"; ensuring the inaccessibility of conductive parts for accidental touching; use of insulation; use of methods of collective protection against electric shock: protective grounding, zeroing and automatic shutdown; periodic check of grounding resistance; control and prevention of insulation damage.

e) In order to eliminate electromagnetic radiation and EMF when working with outdated models of computer monitors, the use of modern computer technology is provided, in particular, the replacement of monitors with an electron beam tube with LCD monitors or TFT monitors.

f) The main principle of psychological help should be the activity of psychoprophylaxis, which consists in the formation of psychological stability of the individual, which ensures the prevention of the emergence of crisis states of the personality, neuropsychological disorders and disorders, that is, prevention not only when a person turns to a psychologist, but also active permanent psychoprophylaxis in the form of a special or psychological training, psychodiagnostic examinations, observation and preventive use of various psychological means and methods of correction, one of which is respiratory psychotechnologies.

For the practical implementation of psychological assistance measures, programs and optimal methods (means) of rehabilitation should be developed, which include organizational and methodical issues, personnel (staff) and resource (material) support.

The minimum structure for the provision of crisis services is a "hotline", offices for social and psychological assistance are crisis departments. This fully applies to all forms of crisis psychological states of the individual.

7.4 Measures to ensure industrial sanitation and occupational hygiene

In order to ensure optimal parameters of the air environment, the fulfillment of requirements is provided ДСН 3.3.6-042-99 "Sanitary norms of the microclimate of industrial premises" [30] and ГОСТ 12.1.005-88 (1991) "ССБТ. General sanitary and hygienic requirements for the air of the working area".

Table 4.1 Optimizing the value of temperature humidity and speed of movement of air masses

Parameters	Optimal	Acceptable
Temperature ºC	20-22	26
Humidity %	40-60	75
Speed of transfer of air masses m/s	0.1-0.3	0.5

To ensure optimal conditions, the arrangement of the water or steam heating system is provided in accordance with ДБН В.2.5-67: 2013 "Heating, ventilation and air conditioning" and installation of a model household air conditioner Samsung AQ24UGF.

To ensure optimal lighting in the workplace, which is standardized according to ДБН В.2.5-28-2006 "Engineering equipment of buildings and structures. Natural and artificial lighting", as 200 lux provides a device for lateral natural lighting and a system of artificial uniform general lighting. The system uses fluorescent lamps of the LB, LD type with a power of 40 to 80 W, which are installed in PVL-type lamps.

In order to exclude electromagnetic radiation and EMF when working with outdated models of computer monitors, the use of modern computer technology is provided, in particular, the replacement of monitors with an electron beam tube with LCD monitors or TFT monitors.

To ensure the ergonomics of the workplace according to the requirements НПАОП 0.00-1.28-10 "Occupational safety rules during the operation of electronic computing machines", where the prohibition of cluttering the workplace, compliance with regulations regarding the workplace area per employee is specified.

To minimize the negative impact of tension and intensity of work in the work are provided:

- optimal mode of the labor process;
- implement modern methods of psychological relief, which involve.

To increase labor efficiency, measures are applied to optimize the management of the labor organization, which involves a system of trainings, training of the organization's management, methods of effective management, improvement of organizational culture - a holistic system of behavior models, customs, traditions and expectations developed in the organization and characteristic of its members), ensuring stability of the team, employee awareness and transparency of the organization's policy.

The main principle of psychological help should be the activity of psychoprophylaxis, which consists in the formation of psychological stability of the individual, which ensures the prevention of the emergence of crisis states of the personality, neuropsychological disorders and disorders, that is, prevention not only when a person turns to a psychologist, but also active permanent psychoprophylaxis in the form of a special or psychological training, psychodiagnostic examinations, observation and preventive use of various psychological means and methods of correction, one of which is respiratory psychotechnologies. This fully applies to all forms of crisis psychological states of the individual.

7.5 Fire safety measures

The complex of fire prevention measures [31] for a room (office) equipped with personal computers with VDT is developed according to the requirements НАПБ А.01.001-2014 "Rules of fire safety in Ukraine".

Based on the analysis of substances and materials used when working in the room, in accordance with the requirements НАПБ Б.03.002-2007 "Norms for determining the categories of premises, buildings and external installations for explosion, fire and fire safety", a premises (office) equipped with a VDT belongs to productions of category "B" for fire hazard - a space in a premises in which there are solid combustible substances and materials.

Since the premises (office) equipped with fire protection equipment belong to the productions of the "B" category in terms of fire hazard, therefore, according to the requirements ДБН В.1.1.7-2002 "Fire safety of construction objects" it has the II degree of fire resistance.

Among the technical and organizational measures to prevent fires in a room (office) equipped with personal computers with VDT, the following fire prevention measures are provided. On the power equipment, power and lighting circuits, in accordance with the requirements of clause 3.1 " RIEI ", protective devices are installed that turn off the power source from the section of the electric circuit in which a short circuit has occurred.

According to requirements НАПБ А.01.003-2009 "Rules for setting up and operating fire alarm systems and managing the evacuation of people in buildings and structures" and ДБН В.2.5-56:2014 "Fire Protection Systems", the "Signal-VK6" fire and security alarm system is installed in the premises (office) equipped with personal computers with VDT. Which provides detection of heat and smoke signs of fire and the place of fire with accuracy to the location of the sensor.

Accordance with the requirements НАПБ Б.03.002-2004 "Typical rules for the suitability of fire extinguishers" for extinguishing electrical equipment in a room (office) equipped with personal computers with VDT under voltage, carbon dioxide fire extinguishers of the VVK-5 type are provided in the amount of 2 pieces. The distance between fire extinguishers and places of possible fires does not exceed 10 m.

Measures to ensure safety, industrial sanitation, occupational hygiene and fire safety provided for a room (office) equipped with personal computers with visual display terminals ensure safe and comfortable working conditions for personnel.

Conclusions:

1. The main legislative acts on labor protection are the Laws of Ukraine: "On labor protection", "On health protection", "On fire safety", "On ensuring the sanitary and epidemic welfare of the population, the Code of Labor Laws (CoLL) and state inter-industry and industry normative acts, which are mandatory for all state and non-state institutions throughout the territory of Ukraine.

2. According to a large amount of collected statistical information, one of the main causes of electrocution is electric shock, so it is an important aspect to pay sufficient attention to the establishment and observance of occupational safety rules when working with electricity. Attention was paid to the calculation of contour grounding for the area where the electrical equipment is located.

3. The main groups of preventive measures to avoid injuries are considered. Means and measures of protection against electric shock, injuries and accidents are highlighted. The main technical and organizational measures to avoid fire were considered. The structure of the fire extinguisher as a primary means of fire extinguishing is considered.

CONCLUSIONS

The use of unreliable flight information about the parameters of the angular orientation (roll and pitch angles) when flying in the zone of active radio interference can lead to the loss of the UAV. Especially if the estimates of the unobservable components of the state vector in inertial satellite systems are obtained using the extended Kalman filter, because GNSS outages significantly distort flight information.

The proposed options for automatic control loops using only information from sensors for direct measurement of flight parameters significantly reduce the risk of loss of the UAV when flying in the zone of active interference.

Analyzing the statistical values of the rates of change of the roll and pitch angles, which are the angular parameters of the UAV flight control laws that are not involved in the formation of the UAV flight control laws, on steady-state straight flight sections, it is possible to estimate the errors of the primary information sensors.

The reconfiguration of the control loops does not affect the algorithms for solving SINS navigation problems, in particular, the algorithms for generating the matrix of direction cosines.

Studies of the proposed control loops have shown their high efficiency.

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