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MODERN ASPECTS
OF HELICOPTERS' MODERNIZATION

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The monograph will consider the features and possible ways to modernize the avionics of helicopters. The article examines the general provisions on the ergonomic aspects of the design of helicopter aviation equipment, in order to improve the ergonomics of its use in the operation of helicopters.

Recommended for specialists, post-graduate students and students specialising in 173 – «Avionics» and 272 – «Air transport», and in other related professions.

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Appeal to Readers…

The given monograph is logical extension of " Modern aspects of helicopters' modernization" by S.M. Boiko, V.H. Romanenko, Yu.V. Stushchanskyi, M.O. Nozhnova, V.M. Doludariev, Ya.S. Doludarieva, I.M. Koval and N.A. Koversun.

Another monograph. Not the first. This is a continuation of the ongoing research in the field of aircraft avionics, namely helicopters. The authors of this monograph are scientists from the National Aviation University, Kremenchug Flight College of Kharkiv National University of Internal Affairs and Kremenchug National University named after Mykhailo Ostrogradsky, my colleagues, like-minded people and friends who are directly involved in training aviation technicians and helicopter pilots.

What is the purpose of writing this monograph? What is the target audience? We did not consider these issues while working on this monograph. The monograph is aimed at a wide range of specialists - electricians, avionics, students, cadets, graduate students and more.

We also hope to be satisfied with the work done and will be happy if someone finds this work useful. Of course, readers can either praise or criticize him. In any case, we hope that our readers will appreciate our efforts.

It so happened that the publication of the monograph was timed to the anniversary, the 60th anniversary of the founding of the world-famous Kremenchug Flight College, which is now part of the Kharkiv National University of Internal Affairs.

S. Boiko and team of authors

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LIST OF ABRIVIATIONS

AC – aircraft;
ASS – air signal system;
AV – avionics;
CC – control cell;
CL – code link;
CWS – critical warning system;
DC – digital computer;
DMA – direct memory access;
DME – rangefinder;
ECK – engine control knob;
EGPWS – Enhanced Ground Proximity Warning System;
EIS – electronic indication system;
ESD – external storage device;
ET – electronic tablet;
FOCL – fiber optic communication line;
GPWS – ground proximity warning system;
HMDS – helmet-mounted display system;
HSC – heading station corner;
ICRT – indicator on a cathode ray tube;
SS – special software;
TCCS – traction control computer system;
VOR – radio navigation system;
WRS – weather radar station.

INTRODUCTION

Despite the fact that the development of ground approach warning systems began in the mid-70s, collisions of aircraft with the underlying surface, according to the CFIT (Controlled Flight Into Terrain) concept, continue to be the most common cause of accidents. On average, four incidents occur throughout the world per year for this reason. In recent years, it has become possible to significantly expand the functionality of such systems by adding early warning methods of approaching the ground (the function of assessing the terrain in the direction of flight, warning of premature altitude reduction) and indicating the degree of danger of the surrounding terrain on the pilot's display. This allows you to increase the time provided to the crew to make decisions and correct the situation. The EGPWS system was first introduced in 1996. An analysis of flight incidents involving a collision with an underlying surface or obstacle showed that the installation of EGPWS Ground Warning Systems could prevent 95% to 100% of them. In order not to confuse GPWS with EGPWS, it is better to use the term TAWS - Terrain Awareness Warning System for advanced systems. This term is now used in official documents of ICAO, Europe, USA [1].

Since January 1, 2005, ICAO has introduced a mandatory requirement for an early warning system for approaching land on all aircraft with gas turbine engines with a maximum authorized take-off mass of more than 5700 kg or authorized for transportation of 9 or more people. In Europe, the availability of TAWS (EGPWS) is mandatory from January 1, 2007.

As a matter of fact, this is a well-known system for preventing a collision between an airplane and the earth's surface, but it is somewhat modernized and improved. Previously, the system was not called EGPWS, but SSDSAG (Signaling System for Dangerous Speed of Approach to the Ground) – in the West is an analogue of GPWS (Ground Proximity Warning System-System of Warning of Approaching the Earth). Not far away is a new system, but an analogue of SSDSAG, however it is not completely solved the problem of collision of aircraft with the earth's surface. The problem of the SSDSAG (GPWS) is that there is not enough time for the reaction after it is triggered, because it was triggered by the fact of convergence, there was no "forecast", and therefore it was ineffective.

The thesis is dedicated to improving the efficiency and modernization of the early warning system for approaching the aircraft to the earth's surface, by replacing the indicator with a touch-sensitive liquid crystal tablet navigator. For this purpose, the purpose and principle of operation of electrical equipment, early warning systems for collision with the ground, the installation of the indicator on an aircraft, modernization and reliability are investigated [2].

The prevention of collisions with the surface of the earth during the controlled flight of civil aircraft has recently become one of the main concerns of the aviation authorities worldwide. According to statistics, it is this type of accident that dominates among the factors that led to the most severe flight accidents. That is why over the past years, a number of organizational measures have been consistently taken aimed at toughening the requirements for on-board equipment of civil aircraft and improving the corresponding on-board systems.

Currently, widely used devices signal a dangerous approach of the aircraft to the surface, based on the readings of barometric systems of air signals (barometric altimeters), or radio altimeters, signals that are converted into appropriate sound and visual warnings. Their development is mainly in the direction of increasing the accuracy of measurements and the rate of change of sensor readings [3].

EGPWS is distinguished by the presence of an extensive built-in database on the terrain, which, according to foreign experts, is a significant step forward compared to conventional GPWS systems that work on the basis of data from an on-board radio altimeter.

From a technical point of view, early warning is carried out by displaying on the screen a multifunctional indicator of data on the height of the profile of the terrain over which the plane flies.

Therefore, currently there is an urgent scientific and technical problem of choosing the type of device for displaying flight information [4].

CHAPTER 1
DEVELOPMENT OF THE GENERAL STRUCTURE AND THE GENERAL SYSTEM ALGORITHM

The chapter analyzes the basic requirements for GPWS systems with existing regulatory documents. The basic requirements for the modes and functions of GPWS are given, the existing experience of manufacturers of this class of equipment in terms of implementing these requirements is analyzed. Existing options for the construction schemes of GPWS systems as part of the on-board equipment complex are considered. A new version of the design of the system calculator is proposed, which has several advantages. The analysis results are the basis for the developed system [5].

1.1 Analysis of the general requirements for GPWS

The main requirements for the characteristics and modes of GPWS are reflected in the documents

The International Civil Aviation Organization (ICAO), the international corporation ARINC, Inc., the Radio Technical Committee for Aviation RTCA, and the United States Federal Aviation Agency (FAA) [6].

ICAO requirements are formulated in:

– Amendment No. 27 of Annex 6 of Part 1 of the Convention on International Civil Aviation,

– Letter of recommendation AN 11/1 1 / 26-01 / 61 of June 15, 2001.

The requirements are for informational purposes, indicating the timing of the introduction of flights without a collision avoidance system with a function of assessing the terrain in the direction of flight. Documents do not boil the system requirements and refer to the document of the US Federal Aviation Administration TSO-C151A

ARINC, Inc. made recommendations in the documents [7]:

– ARINC 763, "Terrain Awareness And Warning System (TAWS)." Recommendations December 10, 1999.

– ARINC 723, "Ground Proximity Warning System (GPWS)" Recommendations or January 11, 1988.

– ARINC 429, "Digital Information Transfer System" Recommendations, September 1, 1995.

– ARINC 708, "Airborne weather radar". Recommendation November 15, 1999.

– ARINC 646, "Ethernet Local Area Network". Recommendations December 8, 1995.

These regulatory documents are not binding and are of a recommendatory nature. Documents represent the generalized experience of companies that install, operate and maintain systems. In general, recommendations are aimed at ensuring interchangeability of equipment from different manufacturers, ease of operation and maintenance. In documents Specifies the features that must be considered for the possibility of docking with other on-board systems (interfaces, types and levels). no power supply voltages, weight and size parameters, etc.) When developing the system, these protocols were used to develop protocols for information interaction between the system and the aircraft's onboard equipment. Recommendations regarding the necessary system controls were also taken into account. The requirements of the RTCA committee are reflected in the documents.

– DO-160A, "Minimum Performance Standards Airborne Ground Proximity Warning Equipment" Requirements of May 27, 1976 Documents of this organization are normative in nature. DO-160A stipulates the minimum requirements for the operation of signaling modes of modes 1-5 for systems of class SPS. The requirements for the volume and duration of the speech alarm The type of alarm boundaries for modes 1-5 is provided that provides minimal protection. The developer is given the right to change the alarm boundaries with a restriction that the system must provide a level of protection no less than that provided document DO-160A For modes that have both emergency and warning signalization, restrictions are only given on the boundaries of the alarm. The document decorates that some modes should be active only at certain stages of the flight. Do not decrease mode 3 should be issued during take-off, initial climb and departure to the second circle, while mode 4 warnings about non-landing configuration of aircraft only during approach, however, an algorithm for determining the flight augmentation is not proposed.

– DO-160D, "Environmental Conditions and Test Procedures for Airborne Equipment" The document reduces the criticality categories of the commercial equipment to external factors and describes methods for confirming compliance with these categories. The requirements were taken into account when designing the hardware of the system - DO-200A, Standards for Processing Aeronautical Data. The document describes the rules for creating and maintaining databases. In this work was not used.

United States Federal Aviation Administration (FAA) Transportation Documents – TSO-C151A "Terrain Awareness And Warning System" November 29, 1999 Basic document for minimum functional specifications for TAWS Class Early Warning Systems.

This document is the main and almost the only normative document regarding the requirements for the functionality of the GPWS system. It says that the core of the system should remain the "old" SDRP modes (GPWS), implemented taking into account the requirements of DO-161A [8].

– Mode 1. Excessive rate of decline;

– Mode 2 Dangerous approach speed with the underlying surface;

– Mode 3 loss of altitude after take-off;

– Mode 4. Approaching the underlying surface in a configuration that does not match the landing;

– Mode 5 Significant deviation below the glide path.

There are no requirements for the implementation of regime 6.

In addition to these modes, in order to eliminate the main disadvantages of HPS class systems, such as delayed signaling and insecurity of aircraft in some situations, new modes and functions should be implemented

– Mode 7. The function of assessing the terrain in the direction of flight;

– Mode 8 Warning of premature decline;

– the function of forming and displaying an image of the nature of the underlying surface on the indicator.

This additional functionality should be implemented through the use of digital terrain databases and an aeronautical database. It is emphasized that the isolation of old and new functions should be ensured, i.e. the impossibility of implementing new functions for one reason or another should not lead to termination work of old functions and vice versa. The document allows, but does not boil, the ability to change the boundaries of old modes for better compatibility with new functions and minimize false alarms. Thus, the question arises of studying the principles of constructing the boundaries of signaling modes taking into account the availability of new sources of information [9].

In part 7 of the mode, it is said that the equipment must provide a view ahead of the aircraft within the predefined working protective space and timely signal if elements of the underlying surface fall into this space. The function is necessary throughout all phases of flight, including the evolution of the aircraft. The space should be built from the estimated range in the direction of flight of the aircraft, the distance on both sides of the flight path and a predetermined distance down from the height of the aircraft ate, in Depending on the vertical flight path, the working space should vary depending on the flight stage, the distance to the runway and the required height above the underlying surface in such a way that the aircraft is protected at the lowest possible level of false alarms. The size of the working space in horizontal plane should increase laterally if rotation is necessary. The workspace must take into account the accuracy of navigation sources.

For sub-mode 7, two sub-modes are distinguished. The first sub-mode (warning of insufficient reserve by height) should provide the appropriate signaling when the aircraft is on a given flight path, but the estimated reserve of height above the underlying surface is not safe for a particular flight phase. The required height of flight over obstacles should be selected based on the rules of aircraft operations. The document stipulates the minimum and maximum reserve in height at which and the alarms of this sub-mode will be issued depending on the flight phase. The following stages of flight, the cruising phase of the flight, flight in the area of the aerodrome, landing are highlighted, and considerations are given regarding the logic of determining the stages of flight. The text also briefly describes the minimum list of tests that are necessary when testing the system to confirm the correct operation of the sub-mode.

The second sub-mode (warning of the threat of a collision with the ground) should provide the appropriate signaling when the aircraft is currently below the height of the underlying surface along the assumed horizontal flight path. To implement this sub-mode, specific requirements are not given [10].

The document does not stipulate requirements for regime 8. It is recommended that the developer take into account existing flight rules, propose their own signaling boundaries, and develop criteria for their assessment.

As regards the relief display, it is boiled that the information about the underlying surface on the on-screen indicator should be plotted relative to the location of the airplane so that the pilot can determine the azimuth and the distance to the underlying surface of interest. In addition, the display of the underlying surface should be oriented according to the course or ground speed. The difference in the difference in the heights of the elements of the underlying surface relative to the height of the aircraft (above, below) should be well distinguishable. a surface below 2,000 feet below the aircraft may not be displayed. The elements of the underlying surface that cause the appearance of an alarm should be different from the elements that do not cause an alarm in accordance with the levels of warning and alarm [11].

The document also specifies the requirements for speech signaling (a specific phrase) and visualization, signaling priority by mode, general requirements for terrain data bases (discreteness of storage of elevation elevation values). The document introduces two classes of GPWS Class A equipment, for which the performance of all GPWS functions should be used on airplanes with the number of passengers more than 6 And class B for small airplanes and a number of restrictions on the necessary for the implementation of functions In accordance with the task the developed system should belong to class A and include all the necessary functions [12].

Thus, the document describes the most general requirements, providing the developer with relative freedom in choosing a specific implementation of the algorithms for the functioning of the system and methods for checking them. The main condition is that the resulting characteristics are no worse than those given in the standard.

It should be noted that, stipulating a specific implementation option of the system (based on the use of a database of the underlying surface and airports stored in the on-board computer), the document does not prohibit the use of other physical principles to ensure the protection of aircraft, for example, radiolocation, however, when using alternative methods the developer is required to prove an equivalent level of security and provide the necessary techniques [13].

– AC No 23-18 "Installation of Terrain Awareness and Warning System Approved for Part 23 Airplanes" Recommendation Circular June 14, 2000.

– AC 25-23, "Airworthiness Criteria for the Installation Approval of a Terrain Awareness and Warning System (TAWS) for Part 25 Airplanes" Recommendation Circular May 22, 2000.

– Final Rule 14 CFR Parts 91, 121, 135, March 2000.

These circulars, in spite of their advisory nature, are actually mandatory. In fact, the contents of these circulars repeat the requirements of TSO C151A. They additionally boil that the aircraft height used for the purposes of mode 7 (orthometric height) must be determined by completing at least, data from the satellite system and barometric altimeter. For this reason, an algorithm for determining the orthometric height is considered in the work.

1.2 Aviation events and flight safety

Flight safety and aviation security play a paramount role in the operation and development of international air transport. States have the primary responsibility for ensuring regulatory control in the field of flight safety and aviation security, regardless of any changes in the economic regulation system [14].

According to the International Civil Aviation Organization, the relative level of flight safety in the domestic civil aviation industry is much worse than the global average. The problem of aviation security is very important because it has significant social and economic disadvantages.

Moral damages in connection with injury or loss of life, loss of image of air transport companies, loss of trained professionals and the need to replace them in society, economic losses associated with the need to compensate for the consequences of air accidents, development and implementation of measures to prevent the causes of traffic accidents and other – represent the components of these losses. However, air safety is not only about passenger safety. This concept also applies to the safety of transporters, the population in the area of possible aviation accidents, cargoes, vehicles and structures, and the environment that may be affected by aviation accidents. Flight safety issues have remained and will remain relevant as long as aircraft of various purposes are operated, including civil aviation aircraft. There is a constant improvement of aircraft construction, methods and methods of their operation, training of crews, problems of airworthiness, survivability of aircraft, safety of air traffic, which constantly remains in the view of representatives of operating enterprises and scientific institutions. These processes most clearly highlight the problem of a lack of new ways of managing flight safety processes, identifying threats and relevant sources of air travel hazards, and will continue to become more relevant. In such circumstances, it is urgent to develop a new list of criteria (indicators) for aviation safety and its legislative consolidation [15].

The problem of flight safety, despite the rapid scientific and technological progress in the field of aviation technology, has become of exceptional social urgency in our time. This is explained by the number and nature of accidents and catastrophes. In 2010, 29 aviation events were recorded with multi-engine aircraft. As a result of these catastrophes, 831 people were killed in planes and 6 people on the ground. Annually, from 2000 to 2009, an average of 31 aviation events took place, killing 810 people. According to the data received from the NBRCA (National Bureau of Investigation of APs and incidents with civil aircraft), in 2017, during the operation of civil aircraft (aircraft) of Ukraine for passenger and cargo transportation, aviation, training and flying and operation of general aviation aircraft, which are entered in the State Register of Civil Aircraft, occurred: 5 catastrophes (2 of which - in the performance of aviation works and training flights and 3 of general aviation aircraft); accidents (1 of which in the performance of ACH, 1 in the aircraft of general aviation and 1 in the performance of freight); serious incidents; 41 incidents; 1 ground damage to the aircraft. In addition, during the analyzed period, there were 2 catastrophes in which 2 persons died while performing unauthorized private flights of airplanes not entered in the State Register of Civil Aircraft. In 2017, 64 events involving foreign civilian aircraft occurred in Ukraine [16].

With each passing year, the requirements for ensuring the safety of civil aviation aircraft are getting higher and higher. There are good reasons for this:

a) the fleet of aircraft in many countries of the world has grown significantly;

b) the number of international airports has increased;

c) the intensity of flights on both local and international routes has increased;

d) increased number of aviation accidents related to collisions of the aircraft in the air, on the ground, with the ground surface during landing, with artificial obstacles and the ground surface in flight;

e) the human factor – insufficient training of the air traffic control dispatching staff and, as a result, erroneous crew commands led to serious aviation accidents;

e) Insufficient equipment of the Armed Forces, especially small aircraft, with adequate equipment for enhancing airborne power, both on land and in the air.

The Mi-8 helicopter is the main type of aircraft operator in the African continent [17].

Ensuring flight safety at UN missions is a priority and the red line is traced in UN documents, tenders, Derective, etc.

The UN's requirements for aviation engineering and contract staff have increased several times over the short term. This fact has justification, since the number of aircraft of different operators has increased and proportionally increased the number of aviation accidents, dangerous rapprochements in the air, including catastrophes associated with the collision of the aircraft with the earth's surface and artificial obstacles on it.

1.3 General characteristics of the early warning system for approaching the ground

The current stage of development of the helicopter industry is characterized by the active equipping of aircraft cockpits with multifunction indicators (MFIs), connected with on-board digital-analogue devices and allowing the pilot to present information about the pilot-navigation parameters of the helicopter. The use of multifunction MFI indicators opens the possibility of creating cabs fundamentally different from the traditional configuration and presentation of information.

EPEWS (Earth Proximity Early Warning System) The ST3400H is designed to alert the crew of a possible situation that could result in the accidental collision of a helicopter with a ground or water surface, as well as artificial obstacles. Prevention is carried out - by issuing speech and light signaling, as well as by forming visual information about the nature of the litter surface on the screen of the processor-indicator SANDEL ST3400H, based on electronic databases (DB) of the terrain, artificial obstacles and airfields [18].

The principle of EPEWS operation is to process information received about current flight parameters (helicopter coordinates, altitude, radio altitude, course, etc.) from regular helicopter systems and to provide crew with the necessary graphic, light and sound warning alarms when potentially dangerous for helicopter situation.

The function of estimation of terrain in the direction of flight is to analyze the trajectory of flight of the helicopter with information about terrain relief, artificial obstacles and distances to runways of the airports, as well as the indication of the relief is provided during all stages of flight - departure, flight on route and maneuvering in the zone landing. The EPEWS has built-in hazard alerting features that provide light and voice alerts. All warnings are made automatically.

Limitations of EPEWS [19]:

– the system does not guarantee the presence in the database of all actual artificial obstacles and transmission lines;

– not intended for navigation;

– course indication and path lines are not intended for use on standard departure and approach procedures;

– LOW-SENSE, OBST-ONLY, TACTICAL, OFF-APT should not be used in instrument flight conditions;

– at low air temperature it is necessary to warm up the cabin to a temperature not lower than minus 15 °C before switching on the GPWS;

– do not use EPEWS modes (block with Mute button): for flights at high latitudes (more than 70 ° N and 70 ° N); when landing at airports not included in the database.

Sandel ST3400H HeliTAWS has 5 alarm modes [20]:

1. FLTA (Forward Looking Terrain Avoidance (Alerting) alarm).

It is formed if the predicted flight path of the helicopter, taking into account the current position, altitude, vertical and instrument speed does not provide a flight at a minimum safe altitude above the terrain or obstacle. The alarm sounds before the alarm. However, when you turn towards the height or change the vertical speed, the alarm can be issued without warning. When the FLTA alarm is triggered, the display switches to REL and ARC-view (sector) at a scale appropriate to reflect the threat (typically 1 NM).

"CAUTION" – Alerts (20 seconds before a potential collision). Visual alarm is a yellow circle that indicates a potentially dangerous area that may collide. The radius of a circle around artificial obstacles (towers) is usually equal to the height of the obstacle, because high obstacles imply stretch marks.

Alarm – CAUTION TERRAIN on left and right dashboards. Audible alarm: "CAUTION TERRAIN" or "CAUTION OBSTACLE".

"WARNING" – alarm (10 seconds before a potential collision) Visual alarm **-** a circle in red that indicates a dangerous area that could collide. The radius of a circle around artificial obstacles (towers) is usually equal to the height of the obstacle, because high obstacles imply stretch marks.

Light alarm – WARNING TERRAIN on left and right dashboards. Audible alarm: "WARNING TERRAIN" or "WARNING OBSTACLE".

2. GPWS alarm. Mode 1. Excessive rate of decline.

Formed at altitudes less than 450 m (1500 ') by radio altimeter (550 m (1800') in HIGH-SENS mode) when VV threshold is exceeded (depending on true altitude). Alarm: sound and light.

SINK RATE warning sound and CAUTION TERRAIN scoreboard. Emergency PULL UP sound and WARNING TERRAIN scoreboard.

3. GPWS alarm. Mode 3. Loss of altitude after take-off.

Depending on the sensitivity mode, the alarm is generated at the stage of takeoff with the loss of 40% of the height of the maximum dialed. In NORM and HIGH-SENS mode it is activated at altitude 95 'and deactivated at altitude 299'. SENS LOW – 75 'and 149' respectively. If the height loss is higher than the deactivation height value, no alarm will be issued.

Alarm: sound and light. DONT SINK warning sound and CAUTION TERRAIN scoreboard.

4. GPWS alarm. Mode 5. Excessive downward deviation from the glide slope).

Formed by a deviation of ¾ scale down the glide (KI 206) when approaching ILS:

– at altitude less than 950 '(290 m) – HIGH-SENS;

– at altitude less than 400 '(120 m) – NORM;

– less than 250 '(75 m) tall – LOW-SENS.

Alarm: sound and light. GLIDESLOPE warning sound and CAUTION TERRAIN scoreboard. This alarm can be deactivated in the pilot's menu

5. GPWS alarm. Mode 6. Countdown when descending.

The height reading at descent is in feet in English. The alarm is normal sound. It depends on the sensitivity set. The default values (not disabled) are in bold.

– HIGH-SENS – 400, 300, 200, 100, 50, 40, 30, 20, 10;

– NORM – 300, 200, 100, 50, 40, 30, 20, 10;

– LOW SENS – 100, 50, 40, 30, 20, 10;
– ACT TACTICAL – 50, 40, 30, 20, 10;
– OBST-ONLY – 50, 40, 30, 20, 10.

1.4 Location of GPWS on the helicopter and ergonomic problems

The system indicator (screen) is located on the center panel at the top and is clearly visible to all crew members. The ST3400H is located on the center dashboard.

For two boards – in aircraft commander on the left dashboard, in the second pilot on the right dashboard and in the flight engineer – on the central panel.

Yellow signboard – gives a signal of approaching the earth, red – a dangerous approach to the earth.

There are 5 signal boards [21]:

– CAUTION TERRAIN – on the left and right dashboards;
– WARNING TERRAIN – on the left and right dashboards;
– GPWS FAIL – on the central dashboard;
– GPWS LOW SENS – on the central dashboard;
– TAWS INHIBIT – on the central dashboard.

TAWS network protection machine is located on the left panel of the accessory network protection machine.

Figure 1.1 – Location of GPWS on helicopter

JSC Ukrainian Helicopters supports the UN policy on enhancement of flight safety and the first fulfilled the requirements of the flight safety department and purchases on installation of additional equipment for helicopters of the company for compliance with requirements, enhancement of the level of flight safety and competitiveness.

The practice and analysis of flight operations with EPEWS equipment shows that the money invested in the installation of this equipment is justified – the safe execution of tasks with the correct and skillful use of the system will increase many times over [22].

The main task of the instructors and lectors is to qualitatively prepare the flight crew theoretically and practically for admission to work with additional installed equipment.

However, as practice and experience have shown, the presence of an EPEWS on an aircraft does not guarantee the exclusion of aviation accidents.

At about 7 pm on January 25, 2018, a plane crash occurred in Kremenchug: a helicopter crashed into a TV tower. The whole crew died as a result of the incident. The helicopter flew into the television tower of the local TV channel "Visit", fell to the ground, after which a fire broke out. There were 4 people on board. The helicopter was owned by the Ukrainian Helicopters Company. The crew was undergoing training, there were flights between night vision devices.

According to the investigation of aviation accidents, it was the human factor that caused the crash of the helicopter. Due to the difficult weather conditions, the pilots concentrated their attention on what was going overboard, thereby reducing their attention to the dashboard and not physically noticing the GPWS signal boards, which indicated an inevitable collision. Therefore, the ergonomic problem remains open [23].

In the field of view, there are three areas: the central view, where the most accurate distinction of details is possible; a clear vision where, with a fixed eye, you can recognize an object without various small details; peripheral vision where objects are detected but not recognized.

It is believed that in the aircraft cockpit, without turning the head and eyes, the pilot's observation area, in which he can clearly see, is limited to a body angle of 10°. With the turning of the eyes and, exceptionally, the head, the size of the observation area increases to angles 31 ° left / right and 23 ° up / down. With head rotation and torso tilt, the observation area increases to 53 ° left / right, 42 ° up and 57 ° down. A frequent task of the pilot's activity is information search – finding on the indicator of the object with the given signs. Such signs may be flickering, the particular shape or color of the object, the deviation of the arrow by the permissible value, etc. Search time takes tenths of a second, such as finding a tag on a radar screen

– 0.37 s, reading a letter or number – 0.31 s, searching for simple geometric shapes – 0.2 s. The real object recognition time is about 0.4 s, the image recognition time is 0.9 s for the color image and 1.2 s for the black and white. The reading time of the instrument readings is 0.2-0.8 s. The time of visual determination of the position of AC in space is on average 1.35 s, for devices – 1.55 s [24].

The main way to present crew information is to display it with the help of various instruments, tell-tales and electronic indicators, which are placed on the instrument panels in the cockpit.

Despite the wide variety of aircraft, there are general rules for the location of indicator devices on the dashboards according to the type on the information display.

In modern AC, electronic indicators have become the main means of indication. Unlike a traditional device, typically 1-2, maximum 5-8 parameters are displayed, dozens of parameters and signals can be displayed on the electronic indicator screen, changing each other as needed. Such flexibility, along with good ergonomic qualities, high reliability, efficiency by many criteria (for example, by weight, size, cost, power consumption) have led to the fact that electronic indicators have now captured all the main roles in the cabin, pushing aside traditional devices signaling devices to the periphery of the work area as additional and backup means. Indicators are important but not the only components of the display systems, additional signal boards, indicators, devices, projection indicators can be used to display information on the cockpit, speech messages, sound signals, tactile methods (control knobs, various stimuli on special bracelets etc.) [25].

Consider the layout of the dashboards for the most common case – two-pilot AC (on the dashboard with one pilot, the indicators and indicators are placed in the same way). In the cockpit of the aircraft with two pilots in front of them are placed three dashboards CFI – a complex flight indicator, CINI – a complex indicator of navigation information, CISA – a complex information system alarm.

In front of each pilot, zones 1a contain the main aeronautical instruments. Zones 1b accommodate other flight and navigation aids [26].

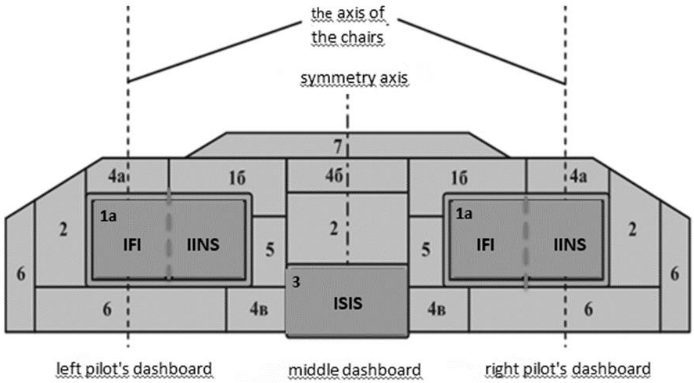

Figure 1.2 – Indication areas for dashboard

On the left and right pilots' panels there is one instance of the following devices: radio altimeter, number pointer M, true air and gauge speed indicator, rotation and sliding indicator, combined angle and attack angle indicator, duplicate altitude meter, distance indicator, clock, seeding and low speed indicators (for helicopters) and more [27].

In the middle of the dashboard in zone 2 are placed reserve flight and navigation indicators: air horizon, navigation indicator or combined pilot and navigation doubler, altimeter, instrument speed indicator, variometer.

In the zone 3 are indicators of the parameters of the power plant. For aircraft with turbojet engines it is: fuel pump lever position indicator, tachometers, exhaust gas temperature indicator, instantaneous fuel consumption indicator, total fuel reserve indicator, oil pressure indicator, oil temperature indicator, fuel pressure indicator, nozzle indicator paging, fuel tank pointer. For helicopters, this group additionally includes: rotation and pitch indicator, transmission control devices.

In zones 4A, 4B, 4B place the signaling lights – respectively, warning, warning and reporting [28].

In zones 5 are position indicators of the control surfaces of the aircraft (flaps, flaps, brake shields, ailerons, stabilizer, rudders, rudder) and position indicators trimming and loading devices. For helicopters set position control devices trimmers (transverse, longitudinal and foot) and the parameters of the exhaust devices.

Zones 6 have indicators for AC systems. For the oxygen system, these instruments are duplicated by each pilot, indicators of other systems (fuel, air conditioning, fire, anti-icing, power, brakes, etc.) may be common if they are visible to both pilots.

In zone 7 there are controls for the pilot-navigation complex (remote control systems).

The most viewed area of the pilot on the dashboards is zone 1a, 1b, and 2. In these zones are the "vital" devices, which the pilot purely automatically draws attention to. Such devices include altimeter, speed indicator.

Therefore, in order to resolve and improve the ergonomic situation, we suggest that the above devices (speed indicator, altimeter) be illuminated, which will be directly related to the EPEWS. When the system issues a threat, the indication will inform the pilots not only via the signal panels, but also through the red or yellow under the instrument lights. In this way, the pilot will be able to pay attention to the apparent threat, to obtain information and to take certain actions to prevent the accident faster [29].

Providing an early warning of the proximity of land, GPEWS solves the problems of the systems GPWS, EGPWS, TAWS / HTAWS, which allows you to install instead of the existing systems SSOS, SPPZ-1, SPPZ-85.

GPEWS, continuously evaluating the height, speed, roll, pitch, as well as the position of the aircraft relative to the earth's surface and artificial obstacles, glide paths, runways, ensures the safety of aircraft and helicopters in accordance with ICAO standards both in the air and at the aerodrome.

The built-in automated control system GPEWS without KPA checks the serviceability of the system on board the aircraft and in the ATB. According to the "black box" GPEWS airlines quickly evaluate the operation of aircraft equipment and the actions of the crew immediately after the flight.

CHAPTER 2
INDICATION OF INFORMATION ISSUED TO PILOTS, EASE OF USE

2.1 Information display methods

The main way to present information to the crew is through various instruments, alarms and electronic indicators, which are placed on dashboards in the cockpit.

Despite the wide variety of aircraft, there are general rules for the location of display devices on dashboards in accordance with the type of information displayed [30].

To date, many different methods for displaying information have been developed, and choosing the appropriate method for a particular case is often a daunting task. The main methods, their advantages and disadvantages, applications are discussed in the section.

On modern aircraft, electronic indicators have become the main means of indication. Unlike a traditional device, usually indicating 1-2, maximum 5-8 parameters, dozens of parameters and signals can be displayed on the screen of an electronic indicator, replacing each other as necessary. Such flexibility, along with good ergonomic qualities, high reliability, efficiency according to many criteria (for example, by weight, dimensions, cost, power consumption) has led to the fact that nowadays electronic indicators have captured all the main roles in the cabin, pushing traditional instruments and signaling devices on the periphery of the working area as additional and reserve means. There are many different requirements for aviation electronic indicators. To satisfy them, the indicator must have certain characteristics. The characteristics required for the on-board indicator are discussed in the section [31].

Indication systems that are currently in operation use indicators based on cathode ray tubes (CRTs). Until recently, CRTs were the only acceptable display component for airborne use. Recently, however, CRTs have lost ground to liquid crystal indicators (LCDs) [32].

Indication methods are classified according to a number of signs.

From the point of view of continuity of indication, it is divided into [33]:

– constant;
– periodic;
– upon request;
– by event.

Constant indication is carried out throughout the flight. This displays the pilot's basic aerobatic parameters – roll and pitch angles, altitude, speed.

In case of periodic indication, the monitored parameter is interrogated and indicated by means of indication from time to time, with a certain period. Indication on request is carried out at the command of the pilot. The requested information is displayed on the indicator and remains there until it is replaced by other information required by the pilot [34].

Thus, for example, information is displayed from aircraft systems – hydro systems, power supply systems, etc. The pilot refers to this information only if there is such a need – at certain stages of the flight or in the event of a malfunction.

Event indication is carried out if any an event that should be reported immediately to the pilot, for example, an important system fails or if a dispatcher message is received via a digital communication channel. In such cases, the necessary information is automatically displayed, the display continues until it is received by the pilot or until the event that caused it ends.

According to the type of information displayed, the indication is divided into [35]:

– measuring;
– predictive;
– given;
– matching;
– team;
– integral.

Measuring information reports on the state of the object at a given time. If this state is monitored using any parameter, then the measurement information is the instantaneous value of this parameter. Measuring information is limited only by a statement of state, leaving the pilot to evaluate, summarize and analyze this information. This type includes the entire main display in the cab.

Predictive information reports on the possible course of the flight and the state of the systems in the future, based on the current situation and the dynamics of its development. Anticipating the situation allows the pilot to accurately and timely control the aircraft and its systems, to avoid the dangers that have not yet occurred, but can occur if corrective actions are not taken. Examples of predictive information include the available distance of flight (based on the remaining fuel supply), the speed of the aircraft predicted in 5-10 seconds (based on the acceleration gained), the alarm about the danger of a collision with another aircraft (based on the direction movement and speed of both his own and another's aircraft) [36].

The specified information reports on flight modes or parameter values that must be achieved based on the task.

For example, on a height scale, a special index may indicate the desired level of the echelon. Such an indication simplifies piloting, maintaining the desired flight mode is reduced to combining the index or arrows showing the measurement information with the index of the set value.

Indication of matching information makes it even easier to manage the facility. Instead of two values – measured and set – the value of their mismatch is indicated, i.e. the deviation of the controlled parameter from the set. A similar indication is used, for example, during landing to represent the deviation of the aircraft from the glide path [37].

Team (director) information combines several parameters in one. Comparison of readings for individual parameters in this case is not required, the pilot only has to carry out the displayed command. The pilot, as it were, ceases to control the aircraft and controls only the arrow on the indicator. On modern aircraft in the director's control mode, the pilot is guided by the readings of two mutually perpendicular bars on the screen. The automatic control system calculates the necessary maneuvers that will allow you to keep the aircraft on a given flight path, the display system shows with the help of the bars the corrective action is required, and the pilot's task is to reduce the bars to a strict crosshair at the starting point of the screen. Command information differs from the given and matching information. Keeping the command bars at zero, the pilot may not be on a given trajectory: the testimony of the bars indicates only that he correctly enters it.

Integral information unites a group of measurement parameters in order to create a single generalized picture that directly informs the pilot about the flight mode. An example of such a parameter is the total energy vector – a value that cannot be directly measured, but with which one can pilot an aircraft.

According to the degree of detail of the information, the indication is divided into [38]:

– quantitative;
– high-quality;
– status.

The quantitative indication transmits information about the value of the monitored parameter. Information is presented in digital form or on a scale.

A qualitative indication does not say anything about the absolute or relative value of the parameter, but shows the direction of its change and proximity to threshold values (Fig. 2.1).

The status indication transmits information about the object according to the yes / no type: working – not working, on – off, etc [39].

In relation to the properties of the image to the properties of the object distinguish between graphic and abstract indication. Graphic display allows you to establish a relationship between the properties of an object or process and its image. An example is the movement of an index depicting an aircraft on a map depicting flown terrain (Fig. 2.1, bottom left) or moving the aircraft symbol up and down in accordance with the vertical movement of the aircraft and left-right in accordance with the lateral movement (Fig. 2.1, top left). Graphic display is easily perceived by the pilot, however, a high degree of visualization in itself is not a guarantee of successful transmission of information, since the visual perception of the flight does not ensure the complete receipt of the data necessary for piloting an aircraft.

In some cases, it is much easier to use the device, which introduced simplifications and conventions in comparison with the visible picture of the flight. In addition, the image of a three-dimensional picture of the surrounding space is still technically impossible, and an unsuccessful attempt to translate it into a two-dimensional indicator leads to distorted perception and is fraught with dangers.

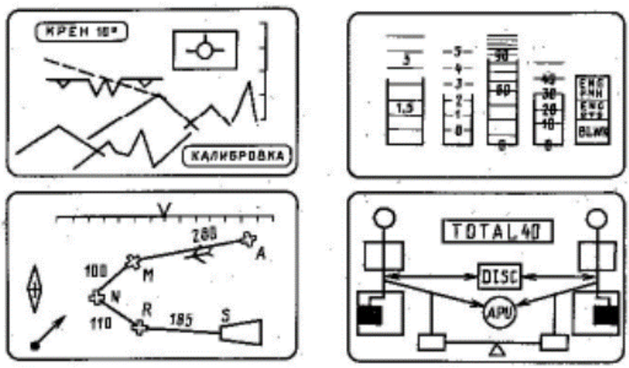

Figure 2.1 – Examples of graphic (left) and abstract (right) indications

An abstract indication is devoid of a similar analogy between an image and an object; it conveys information in an abstract form.

Three main types of abstract indication – scale, symbolic and graphic.

With a scale indication, the value of the parameter is marked on the scale by some pointer – arrow, index, ribbon [40].

In case of sign indication, some alphabet of signs is used for information transfer – numbers, letters, abstract figures, conditional symbols, pictograms. A graphic display depicts objects and their relationships graphically, while, unlike a graphic display, the properties of objects and processes are not reproduced here. Information is transmitted to the pilot in the form of a kind of spatial code. At the same time, the way of perceiving the spatial code has much in common with the perception of the image: after processing this information, a person operates with spatial images. At the same time, it becomes possible to solve complex mathematical and logical problems at the level of imaginative thinking.

Graphic indications include diagrams, graphs, charts, histograms, block diagrams, mnemonic diagrams. Of all these types of graphical displays in aviation applications, only mnemonic diagrams have spread. Mimic diagrams make it possible to simplify the control and management of aircraft systems; therefore, they are mainly used for this [41].

2.2 Information coding

In the case of the use of abstract indication, the problem of optimal coding of information arises. In essence, the entire abstract indication is a code, the knowledge of which is necessary for understanding the information transmitted with its help. Therefore, the perception of such information consists of two stages – detection / recognition and decoding, i.e. awareness of its meaning. In a number of cases, and for graphic display, separate abstract symbols are used, which means that encoding is also present.

By coding, we mean the transformation of the information transmitted to the pilot into a visual form, convenient for quick and reliable perception, without requiring significant mental effort. For coding, sets of simple images are used – numbers, letters, signs, geometric shapes, lines. Additional information can be transmitted by changing the attributes of these primary images – their brightness, color, size, orientation and position on the screen, shape, hatching, fill, type of lines, length and width of lines, blinking frequency [42].

For the same purpose, additional elements are included in the composition of primary images – labels (notation), strokes, etc.

The image attributes used for coding are characterized by the number of gradations, i.e. the number of levels possible for this attribute.

The problem of optimal coding lies primarily in the right choice: 1) the method of coding information, 2) the length of the alphabet of characters 3) the number of gradations of pictorial attributes.

The choice of these characteristics of the code is determined by the nature of the problem being solved: a tacharacteristic that is effective in solving one problem may be ineffective in solving another.

In most cases, giving the image some similarities with the object allows to increase the speed and accuracy of distinguishing and recognition.

It is also necessary to take into account the habitual associations of a person, his worldly and professional experience [43].

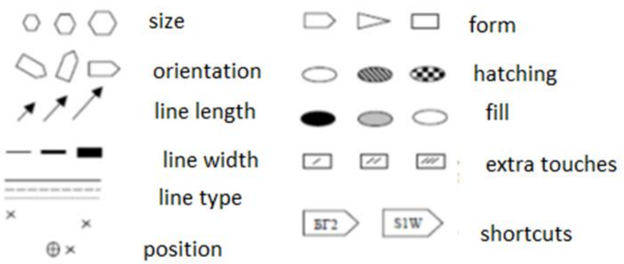

Figure 2.2 – Encoding methods

Most often, the size of the displayed symbol or its brightness is well associated with the size of the object or its importance. The size of the symbol is used to transmit information if the density of information on the screen is low. At the same time, neighboring sizes should differ by no less than one and a half times.

The spatial orientation of the symbol can be used to convey the direction of movement. However, it should be borne in mind that the perception of the image orientation depends on the tilt of the head, the position of the body, the accelerations acting on the person. Therefore, the reference direction should be shown on the screen and the image should be oriented relative to the vertical or horizontal axis of the screen [44].

To attract attention, the symbol flashing frequency is well suited.

If possible, only two states of the symbol should be used: blinking does not blink, although if the information is displayed in the central part of the field of view, a person freely distinguishes up to 4 different blinking frequencies. The blinking frequency should be selected in the range of l-5 Hz with a duty cycle of 2 (in each cycle, the symbol is displayed half the time, half not). The text should flash with a frequency of no more than 2 Hz, while in each cycle it should be indicated 70% of the time, and 30% absent. In all cases, it is necessary to provide the ability to turn off blinking, and where possible, synchronize all blinking image elements in the cockpit to exclude the strobe effect of movement.

To improve character recognition, increase the likelihood of error-free reading of information and reduce the reading time, it is advisable to encode various image elements with color. Color allows you to distinguish characters even if the brightness of the characters and background are the same, but their color is different. Color effectively separates characters when they cannot be spatially separated. Color reduces search time. The results of the studies show, for example, that when indicating the air situation, color helps to identify possible threats more quickly and with fewer errors. Each of the flowers has its own emotional coloring. So, red means danger, orange means warning, yellow means attention, green means peace [45].

When choosing a color, it must be taken into account that for error-free recognition of color signals there must be a certain number of color thresholds between them, and the number of simultaneously used colors should not exceed 5, including white. The following limitations inherent in color perception in humans should also be considered [46].

1. Color improves the characteristics of the display system only if the viewing angle corresponds to the zone of color perception of the eye within a solid angle of 30-40 ° relative to the line of sight of the eye.

2. Color is an effective means of attracting attention (signaling), but only in low light. In high light conditions, in addition to color, other methods of attracting attention should be used: moving the symbol; shape change, for example, outlining the frame around the current parameter value; short flashing characters (up to 10 s).

3. With eye fatigue, visual acuity to red decreases and the distinguishability of green and blue colors decreases. Therefore, symbols indicating critical parameters or events should differ from normal symbols in addition to color by some other distinguishing feature (size, shape, location, etc.).

When encoding important information, you should use more than one attribute (for example, color, size and shape at the same time).

The length of the alphabet of signs and the number of gradations of pictorial attributes should not be too large, otherwise errors occur when decoding the transmitted information. In the case of using alphanumeric characters, the length of the alphabet must not exceed 50, when using abstract characters, they should be no more than 8-16.

Most of the signs a person is able to distinguish if some associative signs are the basis of their construction. Then the alphabet can reach several hundred characters.

The recommended number of gradations for various image attributes is given in Table 2.1.

Table 2.1 –Number of gradations for different image attributes

Image attribute	Number of gradations
Colour	3-10
the size	3
orientation	4-8
brightness	2-4
contrast	2-8
flashing frequency	2-4
type of line	3-8
line length	2-4
line width	2-3
linear arrangement	3-5
two-dimensional arrangement	4-9

2.3 Indicator Characteristics

On-board indicators placed on the dashboard in the cab crew, are characterized by a number of parameters – geometric, lighting, mass and others. Key features include [47]:

– the shape and size of the screen, and in the case of a rectangular screen – the ratio of its sides (aspectratio);

– allowable viewing angles;

– resolution;

– the shape and composition of the pixel;

– image brightness, uniformity of brightness across the screen area, the ability to adjust the brightness;

– image contrast;

– color options;

– screen reflection coefficients;

– frequency of image regeneration;

– image reproduction accuracy, geometric distortion;

– used power supply, power consumption;

– weight and dimensions;

– MTBF.

In addition to the listed characteristics, indicators differ in their capabilities, primarily:

– the presence of a built-in computer – a symbol generator;

– the ability to display a video image from an external source and the ability to overlay other information on this image [48].

2.4 Shape and screen size

Existing on-board indicators have a square or rectangular screen. This form is caused both by technological limitations of the flat panel technologies used, and by considerations of the convenience of the layout of indicators on the dashboard.

The square shape of the screen, i.e. the aspect ratio (horizontal to vertical) of 1: 1, is more preferable for indicating the map and other information in the limited space of the dashboard. Most on-board on-screen indicators of the first generations had a square screen, this format was also approved by aviation standards. Recently, however, cost considerations have come to the fore and the situation has changed.

Due to the fact that the development of an elemental display base specifically for aviation is too expensive and does not pay off for the small needs of this market segment, the developers of indicators are oriented to the use of modified or strengthened commercial display panels, which are used in portable computer displays and have a 4: 3 format. Therefore, at present, the aspect ratio of the screen is 4: 3 as an informal standard for aviation indicators. For indicators of small and medium size, a portrait arrangement of the screen is often used, in which the longer side is vertical (3: 4 format), for indicators of large size, landscape, in which the long side is horizontal (4: 3 format). Some indicators show a video image in a 4: 3 television format, and the characters are drawn in a 1: 1 format.

The screen size of on-board electronic indicators since their appearance on board is slowly but constantly growing. Initially, indicators were installed with small screens – 100x100 mm or 125x125 mm. On modern aircraft, the main indicators have a screen size of 150x200 mm or 200x200 mm. And with the improvement of technology, the size of indicator screens continues to increase. Today, on the latest military and civilian aircraft, you can see indicators with a screen diagonal of 12″ – 14″ (250-350 mm). A similar trend is observed in commercial displays: the moment of appearance in 1988 and before 2000, the diagonal size of liquid crystal indicators with an active matrix increased from 3 to 30 inches [48].

2.5 Viewing angles

The indicator screen can be observed from different angles, while the image quality may vary. Usually, with the observer deviating from the center of the screen to the side, the image quality deteriorates.

The viewing angles of the indicator are the angles at which the image has acceptable quality. They are measured from the normal to the center of the screen, and the quality is characterized by the minimum allowable image contrast. Typically, distances of viewing angles are indicated in two directions: horizontally and vertically [49].

For some display technologies, such as cathode ray tubes, viewing angles are not a critical factor. As for the liquid crystal indicators, which are widely used in the cockpits of modern aircraft, their viewing angles are limited.

Liquid crystal (LC) material is birefringent, therefore, it converts linearly polarized light incident on the polarizer at a nominal angle into elliptically polarized light deviating from the original direction. Since the light is elliptically polarized, the linear polarizer on the front of the indicator directs part of the light incident on it to the side. There are light leaks from the backlight in directions different from the perpendicular to the plane of the screen, and with increasing angle the deflection of the leak increases and, as a result, the image contrast decreases, the brightness and chromaticity deteriorate.

In the cockpit of a fighter, where the pilot, as a rule, is alone and sits close to the dashboard, the requirements for viewing angles are low. For example, on the F-22A, based on the positions that the pilot's head can occupy and taking into account the differences in the anthropometric characteristics of the pilots, the requirements for viewing angles presented to the kindikators were very modest: ±25 ° horizontally and ± 10 ° vertically, i.e. the distance of viewing angles is only 50 ° horizontally and 20 ° vertically. In large cabins of transport passenger aircraft, the requirements for viewing angles are higher. Tentatively, we can assume that the range of viewing angles should be: at least 30 ° horizontally (± 15 °) and at least 30 ° vertically in the cockpit with one pilot, 120 ° horizontally and 60 ° vertically in the cockpit with two pilots [50].

Modern LCDs easily cover these requirements. Commercial displays provide a range of viewing angles of 140 ° -170 ° both horizontally and vertically. The success of aviation indicators is more modest, but the best of them provide a range of 120 ° -130 ° horizontally and 90 ° -120 ° vertically.

Viewing angles depend on the operation mode of the LCD panel. Normally black LCD panels have better viewing angles than normal white ones.

Resolution and information capacity. Resolution characterizes the ability of the indicator to show fine image details [51].

Depending on the adopted method of constructing the image, the resolution can be estimated by the minimum line thickness, the indicator is able to show the length, or by the diameter of the point on the screen that is the minimum possible for this indicator. For indicators with a raster way of constructing an image, such an elementary point is called a pixel. A pixel can be in two states – a luminous item. For computer displays and for TVs, resolution is often estimated based on linear pixel size or line thickness. At the same time, it is expressed in several ways:

a) directly linear in mm;

b) the density of pixels / lines – their number per unit length (1 cm 1 inch);

c) specific number of pixels, i.e. the number of pixels per unit area of the screen (1 cm2 or 1 square inch);

d) the total number of pixels horizontally H and vertical V screens in the form of H x V (for example, 1024x768) or a reference to the standard commercial screen resolution VGA, HVDT, etc;

e) the number of vertical scan lines.

Such methods for evaluating resolution allow comparison indicators among themselves, however, an indication of the linear size of a pixel / line alone or its derivative characteristics does not say anything about whether a person is able to distinguish this particular point / line and therefore how good this indicator is: you still need to know how far the screen is from observer. Therefore, in the general case, the point size or line thickness would be more logical to express in terms of the angular size occupied by this point / line in the observer's field of view and measured in angular units – fractions of a radian or degree. In the particular case of computer displays, the resolution can be reduced to linear dimensions, since the position of the screen relative to the observer is considered fixed and known. Indeed, in the case when there is only one screen directly in front of the human operator, the angular size of the pixel in the center and in the corner of the screen is not very noticeable. For example, when the operator is 40 cm from the 15 ″ screen of the SXGA (1024x768) display, the angular size of the dots in the center of the screen and at the edges differs by 9% and this can be neglected. In the cockpit, where the pilot uses different indicators spaced across the area of the dashboard (and in the cockpit with two pilots, they both can also use indicators on the middle dashboard), the difference in the angular sizes of the points on the indicators can be very significant [52].

Table 2.2 – Resolution Standards

Resolution standard	Image format	Resolution
QVGA	4:3	320x240
VGA	4:3	640x480
SVGA	4:3	800x600
XGA	4:3	1024x768
SXGA	5:4	1280x1024

UXGA	4:3	1600x1200
SDTV	4:3 or 16:9	704x480
HDTV	16:9 16:9	1920x1080 1280x720

By increasing the resolution of the indicator, the image perception quality improves. It is considered good resolution close to the resolution of the eye – 1 ′. Although the eye provides such resolution only in a limited viewing area, this does not mean that outside this zone the requirements for the resolution of the indicator can be reduced: firstly, when transmitting moving images, peripheral vision is sensitive to such resolution, and secondly, the eye can move very quickly within a wide range of viewing angles. The minimum resolution at which the indicator can still be considered acceptable for on-board use is 100 arc seconds [53].

The angular size of the image α created on the retina with a single pixel indicator can be estimated by the formula

$$\alpha = \arctan \frac{S}{D} \tag{2.1}$$

where S is the linear pixel size, D is the distance from the pilot's eyes to the screen.

Based on (2.1), for a typical cockpit board distance D = 750 mm, the pixel size equivalent to the resolution of the eye 1 ′ is 0.21 mm, hence the pixel density should be at least 47 per 1 cm. This means that, for example, an indicator of 6″ x 8″ should have a resolution of at least 768x1024, and an indicator of 9 ″ x12 ″ should have a resolution of at least 1050x1400.

The first industrial LCD indicators in 1988 had a density of 30 pixels / cm, now 47 pixels / cm is considered standard.

In aviation LCD indicators, the density is now 30-50 pixels / cm.

Studies show that to achieve optimal resolution in on-board indicators, a density of 63-67 pixels / cm will be required (for a 9 ″ x12 ″ indicator, this corresponds to a resolution of 1500x2000).

In promising indicators showing moving and complex images, for example, a "tunnel in the sky", a density of the order of 80 pixels / cm will be required.

In three-dimensional auto stereoscopic displays, the appearance of which is expected to be on board in the longer term, in order to maintain resolution, the horizontal pixel density will need to be doubled.

Resolution determines not only the possible image quality, it is a measure of the information capacity of the screen: with an equal screen area, an indicator with a higher resolution can display more information on the screen. In essence, a pixel is an analogue of an information bit, and the more such image units a screen includes, the greater its information capacity.

Therefore, the information capacity I can be defined as the total number of screen pixels [53]:

$$I = H \cdot V, \tag{2.2}$$

where H and V are the resolution, respectively, horizontally and vertically. Information capacity is expressed in millions of pixels – megapixels.

In the computer industry, LCD displays have continuously increased their information capacity for 13 years of existence: from 0.03 Mpixels (VGA) to 1.3 Mpixels (SXGA). High definition television requires a resolution of 1920x1080 (2 megapixels). Monitors with a resolution of 2000x2000 (4 Mpixels) are now available, and the 22 ″ IBM color LCD monitor has an information capacity of 9.2 Mpixels. Aviation indicators follow the path of industrial displays. Now their information capacity is from 0.3-0.4 Mpixels (commercially available development indicators 5-7 years ago) to 1.3-1.4 Mpixels (new indicators with a large screen).

According to forecasts, the information capacity of the main indicators in the future will be about 5M pixels, other indicators on the dashboard will have an information capacity of 1-2 Mpixels. [54]

The indicators discussed above represent information in the form of two-dimensional images. Human visual perception is three-dimensional and, taking into account the third dimension, the human visual system has an information capacity of 1000 megapixels (1 gigapixel). Indicators representing three-dimensional images are already appearing, but for aviation applications they are not yet suitable.

Pixel structure in monochrome indicators, a pixel is the smallest structural unit of an image and does not have its own structure. Color indicators distinguish between a color pixel and a subpixel.

A color pixel consists of at least 3 subpixels of red, blue and green, which together create the desired color. In on-board indicators, a fourth green sub-pixel is sometimes added to the color pixel, which allows you to display a monochrome green image from sensors (optical-radar station, radar) with twice as much resolution, as the number of controlled green dots on the screen is twice as large.

The subpixels can be in the form of a vertical or horizontal strip (stripe), triangle (deltatriad) or square (quad). Studies by Honeywell have shown that the shape of the triangle is optimal for indicators designed for passenger long-haul aircraft. For military aircraft that require an indication of images from sensors, the quadRGBG (RGGB) structure is preferable, i.e. a square with one red, one blue and two green subpixels.

Pixel structure matters with limited resolution. As it increases, the importance of arranging subpixels decreases [55].

2.6 Brightness

Brightness is the main characteristic of light. The magnitude of brightness determines the magnitude of nerve impulses that occur in the retina. The light source or illuminated object will be better visible, the greater the intensity of light emits each element of the surface in the direction of the eye. The brightness of the display element is defined as the ratio of the light intensity emitted in the direction of the operator to the area of the luminous sign.

$$B = \frac{J}{S \cdot \cos\beta} \tag{2.3}$$

where J is the light intensity, i.e. luminous flux emitted per unit solid angle; S is the area of the luminous surface; β is the angle between the plane of the screen and the direction to the observer. Brightness is measured in candelas per square meter [56].

In the general case, the brightness of an object is determined by two components: the brightness of the radiation and the brightness due to external illumination (reflection brightness):

$$B = B_{rad} + B_{refl} \tag{2.4}$$

The brightness of the radiation is determined by the power of the light source and its light output. The brightness of reflection is determined by the level of illumination of a given surface and its reflective properties:

$$B_{rad} = \frac{E \cdot \rho}{\pi} \tag{2.5}$$

where E is the surface illumination; ρ is the reflection coefficient of the surface, π is the constant.

The indicator should provide brightness, allowing reliable reading of information from its screen in all conditions of use. The required image brightness is determined mainly by the level of illumination of the screen: with increasing illumination, the image becomes less distinguishable, "blurred". For computer monitors that are operated in low light conditions (on the ground, a shaded room), the brightness standard is 25-65 cd / m^2, at least 100 cd / m^2 is required to distinguish small details, and at least 300 cd / m^2 for identifying moving images. Significantly higher brightness requirements are imposed on aviation indicators, since illumination increases with increasing height above the ground. For passenger aircraft, illumination in the plane of the dashboard in the area of direct sunlight can reach 70000-78000 lux, however, this level of illumination during a long flight is quite rare and amounts to 2-5% of the total flight time. At the same time, illumination in the plane of the dashboard in the range of 30,000-50000 lux when flying at altitudes up to 15,000 m is quite common. On military aircraft with a transparent flashlight and flying at high altitudes, the illumination in the cockpit can reach 100,000 lux. Since the displayed information is vital, the indicator should be designed for the maximum level of illumination for this aircraft class.

For indicators with a large screen, which mainly use commercial LCD panels, achieving the specified level of brightness is problematic. The maximum brightness of commercial panels is about 300 cd / m^2.

The brightness characteristics of the on-board indicator should take into account not only the possible level of illumination in the plane of the dashboard, but also the fact that the pilot constantly looks from the cockpit to the indicator and vice versa. If the sun hits his eyes, then to distinguish the information on the screen after moving the look into the cabin, eye accommodation is required. To reduce the time of accommodation, the indicator must provide a very high brightness. Studies of the ground in a room with natural light showed that when the view focused to infinity is translated to the indicator screen, the dependence of the re-accommodation time on the image brightness has a pronounced step: at luminances greater than 750 cd / m^2, a noticeable reduction in accommodation time is not observed. Thus, if the operator's work required a constant look from the window and back to the indicator, then such brightness would be enough for a ground. Similar conditions are also being conducted for aviation applications, preliminary results are known, according to which the minimum accommodation time is observed when the indicator brightness is about 1200-1370 cd / m^2.

At night, the brightness level of the indicator should be completely different, usually 0.35 cd / m^2 if night vision goggles are not used and 1 cd / m^2 if used. It is advisable to have a minimum brightness limit of 0.1 cd / m^2.

Since objects with different brightness can fall into the operator's field of vision, the concept of adaptive brightness is introduced in engineering psychology. It is understood as the brightness for which the visual analyzer is adapted (tuned) to a given moment in time. It can be roughly assumed that for images with direct contrast, the adaptive brightness is equal to the brightness of the background, and for an image with inverse contrast, the brightness of the subject.

The best working conditions will be with adaptive brightness levels ranging from several tens to several hundred cd / m^2. Signals with a higher brightness can cause an undesired eye condition. The blinding brightness of images is determined by the size of the luminous surface of the observed object, the brightness of the signal and the level of adaptation of the eye [56]:

$$B_{blind} = B_a + \frac{840}{\sqrt[4]{\beta}}\sqrt[3]{B_a}$$

(2.6)

where β is the solid angle of observation of the luminous surface (in steradians); B_a – adaptive brightness.

To create optimal conditions for visual perception, it is necessary not only to provide the required brightness and contrast of the signals, but also a uniform distribution of brightness in the field of view, so that the perception of information does not require constant re-adaptation of the eyes. The uniformity of brightness is defined as the ratio of the minimum brightness of the luminous elements to the maximum; over the entire field of the indicator, it should be no less than 1: 3. If a change in brightness over the screen area of 50-100% is quite acceptable, then sharp changes in brightness already in 5% are visible to the eye and should not take place. Therefore, sometimes the brightness uniformity is set separately on a large and small area [57].

In the interval between the minimum and maximum brightness for this indicator, it should be possible to smoothly control the brightness. For analogue CRT type indicating devices, the adjustment possibilities were characterized by the number of gradations of brightness. Gradations of brightness differ by 2 times (approximately 1.414 times). This relationship does not have any physical meaning, since the human eye is able to distinguish several times smaller differences in brightness, but it has been established historically. For display devices with a linear brightness characteristic, the representative of which is a CRT, the number of gradations of brightness SOG is associated with the contrast ratio Ki by the following ratio:

$$SOG = \frac{\lg K_i}{\lg \sqrt{2}} + 1$$

(2.7)

Some of the points calculated from this dependence are given in table 5.3.

Modern flat-panel indicators (liquid crystal and others) in most cases are not analog: their brightness can only change discretely, that is, with a certain step. The regulation range of these indicators is characterized by the number of these steps, which has a completely different meaning than for analog indicators, since the steps differ not by 2 times, but in a completely different ratio selected by the developer. In addition to the number of steps, the brightness control is characterized by the law of regulation - linear, logarithmic or other. With the linear law of brightness control, the number of steps is indicated in the form of a ratio, for example, 9600:1, which at a maximum brightness of 700 cd/m^2 means that the minimum brightness step and the minimum brightness value are 0.079600700cd/m^2. For a modern aviation indicator, the brightness control range is considered to be the minimum range of 4000: 1, from 685 cd / m^2 to 0.17 cd / m^2. For LCDs, taking into account the effect of temperature and aging on the lamp, it is desirable to have a much wider control range. Many modern LCDs provide a control range of 10,000: 1, 20,000: 1 and even 30,000: 1 [58].

Brightness control can be done both manually by the pilot, and automatically by the indicator itself. Automatic adjustment allows the pilot to remain silent to maintain the desired image contrast when changing ambient light. To do this, the indicator must have a light sensor. Automatic adjustment is characterized by a range of regulation (usually from 100 to 100,000 lux), response time and regulation law [9].

In promising indicators, a brightness range is expected [59]:

– for passenger aircraft from 3.4 to 750 cd / m^2;

– for military aircraft from 0.1 to 1200 cd / m^2.

The brightness control range should increase to 40,000: 1.

2.7 Contrast

The visibility of objects is also determined by the contrast of their relation to the background. Contrast characterizes the quality of the information reproduced by the indicator and affects the time the operator perceives the indication, the reading speed and the accuracy of identification, which is of great importance in terms of the time deficit allocated to the pilot to review the indicator.

Distinguish between brightness contrast and color contrast. Brightness contrast characterizes the distinguishability of an object against the background in terms of the ratio of their brightness, color contrast – in terms of the ratio of their colors.

There are two types of brightness contrast, direct (the subject is darker than the background) and reverse (the subject is brighter than the background). Working in direct contrast is more favorable than working in reverse contrast.

Quantitatively, the magnitude of the brightness contrast is estimated as the ratio of the difference in brightness of the subject and background to a higher brightness [60]:

$$K = \frac{B_{max} - B_{min}}{B_{max}} \tag{2.8}$$

In direct contrast, Bmax is the brightness of the background, Bmin is the brightness of the symbol;

With the opposite contrast, Bmax is the brightness of the symbol, Bmin is the brightness of the background.

Contrast can be expressed in relative units or percent.

Contrast to 0.2 is considered as small, 0.2-0.5 – as average and more than 0.5 – as high. The optimal contrast value is considered equal to 0.6-0.95.

The minimum value of the brightness contrast at which the eye distinguishes an object (the threshold of contrast sensitivity) is 0.02-0.03 in the case where the direction to the object is known enough, and 0.07-0.09 in the case of unfixed observation.

A great influence on the conditions of visibility of objects is exerted by the magnitude of the external illumination. However, this effect will be different when the operator works with images having direct and reverse contrast.

An increase in illumination with direct contrast leads to an improvement in visibility conditions (the amount of contrast increases). When the contrast is opposite, the light reflected from the indicator screen is added to the emitted light, while the visibility of the characters deteriorates (the contrast value decreases).

Providing the required amount of contrast is only a necessary, but still insufficient condition for normal visibility of objects. One must also know how this contrast is perceived under the given conditions. To evaluate it, the concept of threshold contrast is introduced, which is equal to

$$K_{th} = \frac{dB_{th}}{B_b} \tag{2.9}$$

where dB_{th} is the threshold difference in brightness, i.e. the minimum difference between the brightness of the subject and the background, first detected by the eye, B_b is the brightness of the background [61].

For normal visibility, the magnitude of the contrast K should be 10-15 times greater than K_{th}.

The value of the threshold contrast depends on the brightness and size of objects. With increasing brightness, the value of the threshold contrast decreases, however, when the background brightness is from 0 to 3000 cd / m^2, the threshold contrast is practically independent of the background brightness and color of the glow of the presented information, but is determined only by the angular size of the images (characters, numbers, symbols, geometric shapes, etc.): the threshold contrast decreases with increasing image size, i.e. a larger subject is visible with lower contrasts.

To assess contrast, often instead of luminance contrast, the coefficient of contrast K_i (contrastratio):

$$K_i = \frac{B_{max}}{B_{min}} \tag{2.10}$$

where, with the opposite contrast, B_{max} is the average brightness of the symbol; B_{min} – the average brightness of the background, with direct – vice versa.

The brightness contrast K and the contrast coefficient K_i and are related as follows:

$$K = 1 - \frac{1}{K_i} \tag{2.11}$$

Often K_i is indicated as a ratio, for example K_i = 4.66 is written as 4.66: 1.

The requirements for on-board indicators in terms of brightness contrast in conditions of maximum illumination of 100,000 lux are set in OST1 00345-87 and the manual for the ergonomic support of civil aviation REO-GA-ET (at least 0.5 and 0.6, respectively). To date, these requirements are somewhat outdated. The current level of requirements is reflected in table 2.3 [62].

Table 2.3 – Image contrast requirements

Type of identification	K	K_i
digital	0,5	2
alphanumeric	0,67	3
graphic	0,79	4,66
video	0,82	5,66

For existing aviation LCD indicators, the contrast ratio in high light conditions is 5-8, and in low (at night) – 50-120.

Abroad, such contrast characteristics as: - relative contrast are also accepted

$$K = \frac{B_{max} - B_{min}}{B_{min}}; \tag{2.12}$$

– brightness modulation (luminance modulation, Michaelson contrast)

$$K_{mod} = \frac{B_{max} - B_{min}}{B_{max} + B_{min}} \tag{2.13}$$

Since, for brevity, all four contrast characteristics (K, K_i, K_r, K_{mod}) are simply called "contrast", this often creates confusion.

Reflection coefficient. The background brightness of the indicator devices at a constant level of illumination increases with increasing background reflectance. The reflection coefficient shows how much of the incident light surface is reflected by it. In many ways, it is determined by the color of the surface and in most cases is in the range from 0.07 (black) to 0.9 (white). Since most electronic indicators work in reverse contrast conditions (black background, bright symbols), when the background brightness increases, the image contrast worsens, therefore, when developing electronic indicators, they try to ensure the minimum possible value of the background reflection coefficient through the use of neutral light filters, polarizing films and antireflective coatings. In most cases, these measures adversely affect the brightness of the image: it decreases [63].

The properties of reflected light depend on the structure, direction and shape of the light source, on the orientation and properties of the surface. The light reflected from the subject may be diffuse or specular.

Diffuse reflection of light occurs when light as if penetrates under the surface of an object, is absorbed, and then re-emitted.

In this case, the position of the observer does not matter, since diffusely reflected light is scattered evenly in all directions [64].

The diffuse reflection coefficient depends on the properties of the substance and on the wavelength of light, but is usually considered constant. The diffuse reflection coefficient of modern airborne LCDs is 0.1-0.2%.

Mirror reflection comes from the outer surface of the object.

Unlike diffuse light reflection, specular reflection is directional. The specular reflection coefficient depends on the angle of incidence, however, even with perpendicular incidence, only a part of the light is mirrored, and the rest is either absorbed or diffusely reflected. These relationships are determined by the properties of the substance and the wavelength of light.

The mirror reflection coefficient of the screen should be no more than 0.75%.

The strength of the LCD is the visibility of the image under solar illumination, however, with regard to reflection, they have the same problems as other types of indicators. The LCD screen consists of several layers and each layer contributes its share with respect to specular reflection, in addition, the polarizer is made of plastic and it has a different refractive index than the adjacent glass layer or the adhesive between it and the glass layer [65].

2.8 Color

Currently, all display technologies used in aviation (CRT, liquid crystal, plasma, etc.) demonstrate the possibility of creating full-color indicators.

The range of colors that the indicator is capable of reproducing is determined by its primary colors – red, green and blue, the mixture of which creates all possible colors. The closer the primary colors are to monochromatic, the more saturated they become and the wider the indicator's palette. However, no fixed set of primary colors is capable of creating the entire range of colors distinguishable by man. Moreover, with increasing saturation of the primary color, its spectral range decreases and, as a result, the brightness of the radiation decreases, so the choice of primary colors is always a compromise between the color palette and brightness.

On-board indicators, the color is characterized by the number of gray levels. The number of gray levels of NG is the amount of shade of each of the primary colors (red, green, and blue) that this indicator can show. Mixed with each other shades of tribasic colors allow you to have a palette of (NG) 3 colors. For example, an indicator with 64 gray levels allows you to get 643 = 262144 colors, and an indicator with 256 gray levels has over 16 million colors. Maintaining a linear relationship when dividing the color range by gradation is important.

To indicate symbolic information, it is enough to have only 1-4 mixed colors in addition to the 3 primary colors. When displaying moving, rotating elements, raster indicators like LCD require smoothing, in which case it is necessary to have at least 8 gray levels. When outputting video images and information from on-board sensors, even more gray levels are needed – no less than 16. Modern LCDs rarely have less than 64 levels [66].

2.9 Temporary characteristics

The temporal characteristics of the indication should be selected taking into account the time of inertia of the eye (the time during which the light continues to act on the eye after turning off) and the delay time of the perception of light signals. Time characteristics include: indication delay, information refresh rate, and image regeneration frequency.

For the information used during manual piloting of an aircraft, the refresh rate on the screen should be 15-30 Hz, and the indication delay (including the sensor) should not exceed the equivalent time constant of 100 ms. For many types of display systems, the drawing of the image must be constantly repeated, otherwise it quickly dims and disappears from the screen. So, for example, this is the case with indicators on a CRT: the phosphor in them glows for a very short time. For such systems, one of the main characteristics is the frequency of regeneration of the image on the indicator screen (FRI).

The FRI value should be greater than the critical frequency of flicker. For monochrome indicators, the FRI should be at least 50 Hz, and for color indicators at least 60 Hz. With the television method of reproducing the image, the frequency of the fields / frames should be at least 40/80 Hz for monochrome and 50/100 Hz for color indicators. This is significantly more than required for commercial television (25/50 Hz in the SECAM system, 30/60 Hz in the PAL system).

2.10 Geometric distortion

The accuracy of reproduction of information in the display system characterizes the displacement of the image relative to the coordinate system. The accuracy of reproduction should not be lower than the accuracy of its processing. The characteristic under consideration largely depends on the capabilities of the pilot and the nature of the tasks to be solved. It is recommended that neither one image element did not move more than by an amount equal to 2% of the screen height. Geometric distortion characteristics also include horizontal and vertical image jitter, horizontal and vertical linear distortions. ARINC 421 establishes the following distortion requirements [67]:

– positioning error of not more than 1% of the screen diagonal or 2 mm (which is less);

– the error of the position of one symbol relative to another is not more than 0.5 mm;

– jitter of characters no more than 2 mm;

– positional instability of the entire image is not more than 1.3 mm vertically and horizontally;

– instability of the image size of not more than 1.8 mm vertically and horizontally.

CHAPTER 3
CALCULATION AND IMPLEMENTATION OF EARLY GROUND PROXIMITY WARNING SYSTEM INDICATION

3.1 Chapter Early Ground Proximity Warning System

The system is intended for the timely issuance of a warning message or visual signaling to the flight crew (PC) in the event of such flight situations, the development of which may lead to an unintended collision of the PC with the ground (water) surface, as well as to increase the awareness of the PC crew and elements of the ground surface / or artificial obstacles present in the database that present a potential risk to its existing or predicted path.

EGPWS provides the issuance of voice messages while reducing the predefined fixed heights, the issuance of alarms in excess of the unacceptable value of the roll, the issuance of a warning alarm in the case of premature decline when approaching [68].

The system, based on information about the current flight parameters of the aircraft, the position of the chassis and flaps, the relief of the underlying surface and the presence of artificial obstacles on the surface, continuously analyzes the flight situation and, in the event of a potentially dangerous situation, early forms a warning or alarm.

The ST3400H SRPS system has a connector (Connector P2) on the instrument body, with contacts responsible for displaying discrete external alert information [69].

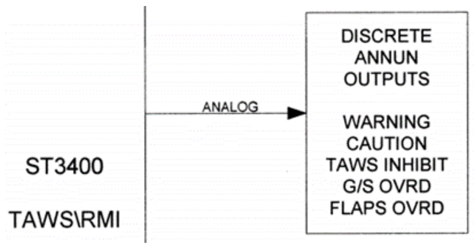

Figure 3.1 – Discrete outputs of the ST3400H system

The type of output depends on the system configuration that can be selected when adjusting the ST3400H. The external menu of the Page 6: OUTPUT PINS indicator menu for selecting the output contacts mode is shown in Figure 3.2 [2].

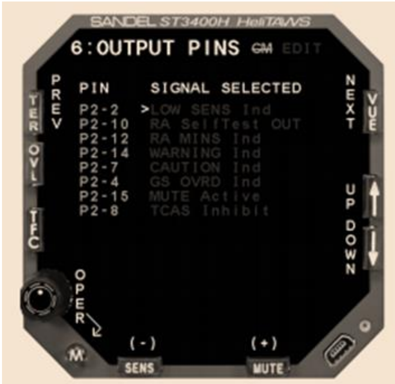

Figure 3.2 – Appearance of the indicator menu to select the mode of output contacts

That is, contacts P2-14 and P2-7 can output alarms (WARNING) and alerts (CAUTION), which are set by default.

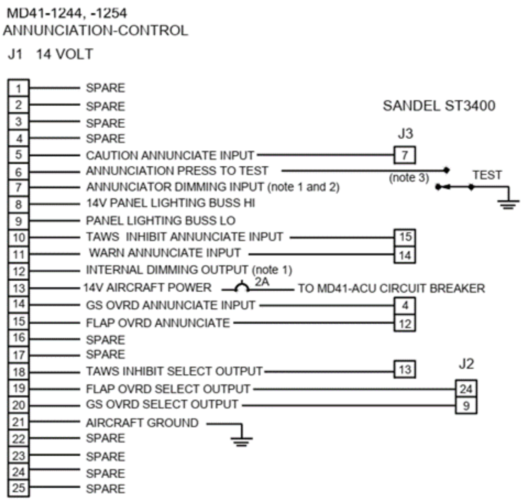

Figure 3.3 – Connection diagram of the control module and alert MD41-1200.

The alarm (WARNING) and alert (CAUTION) are also received by the module from pins 14 and 7 to indicate on the front of the corresponding messages.

Functional diagram of the display device is shown in Figure 3.4.

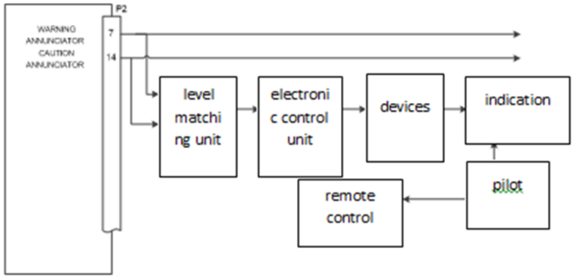

Figure 3.4 – Functional diagram of the display device

Presents electrical characteristics according to the signal types of the ST3400H. So, by the type of Open Drain output, the maximum current is limited to 250 mA (DC), and the recommended load should be greater than 350 kOhm. In addition, to ensure the correct mode without load, it is necessary to ensure a high level by connecting a pull-up resistor with a resistance of 30... 50 kOhm.

3.2 ADC calculation for PIC16F873 microcontroller

1. The resolution of the ADC is determined by the formula:

$$N_x = \frac{1}{n_x} = \frac{1}{2^{10}} = 9{,}766 \cdot 10^{-4}; \tag{3.1}$$

where n_x is the number of code operations.

2. Nominal value of the quantization step:

$$h = \frac{U_{п.ш.}}{2^m - 1} = \frac{5}{2^{10} - 1} = 4{,}88 \cdot 10^{-3}; \tag{3.2}$$

3. To evaluate the quality of the analog signal in the data acquisition channel use the signal-to-noise ratio, which is empirically related to the number of bits and nonlinearity of the ADC used. Increasing the number of discharge m leads to an increase in its resolution, that is, the sensitivity to the level of the input analog signal and directly affect the increase in the ratio C / W. For a real ADC [70]:

$$C/W = 6{,}02 \cdot m + 1{,}76 - \Delta(C/W).$$

Δ (C / W) is a deviation change expressed by the differential nonlinearity of the converter.

$$\Delta\left(C/W\right) = 10 lg^2 (1 + 12\delta^2 dn), \tag{3.3}$$

where $\delta_{дн}$ is the differential nonlinearity of the transformation.

$\delta_{\partial n} = 0{,}1;$

$m = 8;$

$\Delta(C/W) = 10lg^2(1 + 12 \cdot 0{,}1^2) = 0{,}024;$

$C/W = 6{,}02 \cdot 10 + 1{,}76 - 0{,}024 = 61{,}936.$

4. The conversion time for a serial ADC bit type is determined by the formula:

$$T_{np} = m \cdot \tau_0; \tag{3.4}$$

$$\tau_0 = \frac{1}{F_{CLK}} = \frac{1}{50000} = 2 \cdot 10^{-5}; \tag{3.5}$$

$$T_{int} = 10 \cdot 2 \cdot 10^{-5} = 20mc\,s; \tag{3.6}$$

$$F_{CLK} = 50000;$$

5. The sampling rate is estimated by the number of digits and the conversion time of ADC usage:

$$f_d = \frac{1}{T_{pr}} = \frac{1}{2 \cdot 10^{-5}} = 5 \cdot 10^4\,Hz; \tag{3.7}$$

6. The throughput of the acquisition and processing channel (Q) is estimated by the number of digits and the conversion time used by the ADC [71]:

$$Q = \frac{m}{T_{pr}} = \frac{10}{2 \cdot 10^5} = 5 \cdot 10^4\,Hz; \tag{3.8}$$

7. Maximum frequency of signal conversion in the data acquisition system:

$$f_{pr\,max} = \left(\frac{1}{2}^{(m+1)}\right) \cdot \pi/T_{pr} = \left(\frac{1}{2}^{(10+1)}\right) \cdot 3{,}14/2 \cdot 10^{-5} = 76{,}66Hz; \tag{3.1}$$

8. In a digital measuring device, ADCs can be used that monitor the analog signal with a given accuracy until the speed of its change exceeds the conversion tracking speed. Thus, tracking time without using an external sampling and storage device [72]:

$$t_{sl} = \frac{2^{-m} \cdot U_{p.sh}}{T_{pr}}, \tag{3.10}$$

where $U_{p.sh.}$ is the voltage of the full conversion scale corresponding to the range of the input analog signal of the ADC.

$U_{p.sh}$ =5B.

$$t_{sl} = \frac{2^{-10} \cdot 5}{2 \cdot 10^5} = 244{,}141 s; \quad (3.11)$$

9. The frequency response property of an analog information processing channel is largely determined by the value of the ADC aperture time. If this value is normalized, then the frequency response ratio for the harmonic input signal, which reaches the amplitude at the moment of pulse input to the clock input of the converter:

$$K_s = \frac{20\lg\left[1 + \left(\cos\pi \cdot t_a\right)/t_x\right]}{2}, \quad (3.12)$$

10. Aperture time:

$$t_a = \left(\frac{1}{2}^{(m+1)}\right)\pi / f_x; \quad (3.13)$$

where f_x is the frequency of admission of the analog input signal.

$$t_a = \left(\frac{1}{2}^{(10+1)}\right)3{,}14 / 1 = 1{,}53 \cdot 10^{-3}\ s; \quad (3.14)$$

where K_s is the frequency ratio of the frequency response; t_x is the period of adherence to the input analog signal.

$$f_x = 1 \quad G;$$

$$K_s = \frac{20 lg\left[1 + \left(cos 3{,}14 \cdot 1{,}53 \cdot 10^{-3}\right) / 1\right]}{2} = 5{,}02. \quad (3.15)$$

11. Static inverter error:

$$\Delta U = \frac{U_{x\max}}{2}, \quad (3.16)$$

where U_{xmax} is the maximum voltage value of the input analog signal.

$$\Delta U = \frac{0{,}8}{2^{10}} = 7{,}813 \cdot 10^{-4}; \quad (3.17)$$

3.3 Calculation of reliability

Reliability calculations are a procedure for determining the values of the reliability of an object using methods based on their calculation by reference data on the reliability of the object elements, the data on the reliability of analog objects, data on the properties of materials and other information available to the moment of calculations [73].

The calculations determine the quantitative values of the reliability indicators.

Reliability – the property of an element (unit) of a system or product, to remain operable for a calculated period of time under these operating conditions.

Security – the ability of the system to perform the functions they set not only in terms of their implementation and changes of parameters within acceptable limits, but also from the standpoint of preserving the properties and performance of the system, which do not have a direct impact on the performance of the main functions.

The main purpose of calculating and analyzing reliability in systems design is to determine quantitative indicators of reliability for the comparative evaluation of different schemes of identifying the most "weaknesses" in them to take measures to eliminate them, as well as to select measures to achieve the required level of reliability [74].

A feature of the reliability assessment at the design stage is the lack of statistics on the operation of the designed system. Reliability assessment can be made on the basis of long bench tests of the elements. The basis of the engineering methods for calculating reliability is the provision on the exponential law of changing the distribution of time of trouble-free operation of system elements. This allows us to evaluate the reliability of the failure rate of elements, which is a constant value. Data on the magnitude of failure rates – individual elements available in the reference literature, obtained experimentally.

Make a table of the failure rate of the elements:

Table 3.1 – Bounce rate

<table>
<tr><th>Elemenr</th><th>Num-ber</th><th>$\lambda_{cp};\cdot 10^{-5}$</th><th>$\lambda_i \cdot N_i;\cdot 10^{-5}$</th><th>$K_{\lambda_1}$</th><th>$K_{\lambda_2}$</th><th>$K_{\lambda_3}$</th><th>$K_{\lambda_4}$</th><th>$\lambda_{заг}\cdot 10^{-5};$</th></tr>
<tr><td>Resistors (C2-29-0,125)</td><td>14</td><td>0,082</td><td>1,148</td><td rowspan="5">1,07</td><td rowspan="5">1</td><td rowspan="5">1</td><td>0,1</td><td>0,123</td></tr>
<tr><td>Capacitors (К50-5, К53-1А)</td><td>12</td><td>0,15</td><td>1,8</td><td>0,2</td><td>0,385</td></tr>
<tr><td>Diodes (Д9Е, КС156А)</td><td>4</td><td>0,105</td><td>0,42</td><td>0,31</td><td>0,139</td></tr>
<tr><td>LEDs (RL50N, L-81BSCR)</td><td>2</td><td>0,12</td><td>0,24</td><td>0,33</td><td>0,085</td></tr>
<tr><td>Transistors (SS9014, SS9015, SS8050, 2П103Б)</td><td>5</td><td>0,45</td><td>2,25</td><td>0,45</td><td>1,083</td></tr>
</table>

Microcircuit (PIC16F873)	1	0,18	0,18				0,5	0,096
Resonator (РГ-06-14)	1	0,31	0,31				0,32	0,106
Button (П2К-2-2)	1	0,02	0,02				0,21	0,005
Separation	1	0,001	0,001				0,17	0,001
Soldering	119	0,001	0,119				0,5	0,064
Board	1	0,1	0,1				0,1	0,011

The failure rate of the designed device:

$$\lambda=\sum\lambda_i\cdot N_i=10^{-5}\cdot(1{,}148+1{,}8+0{,}42+0{,}24+2{,}25+0{,}18+0{,}31+0{,}02+0{,}001+0{,}119+0{,}1)=$$
$$=6{,}588\cdot 10^{-5} \quad (3.18)$$

Intensity of failures taking into account coefficients:

$$\lambda_{заг}=\sum\lambda_i\cdot N_i\cdot K_{\lambda_1}\cdot K_{\lambda_2}\cdot K_{\lambda_3}\cdot K_{\lambda_4}=10^{-5}\cdot(0{,}123+0{,}385+0{,}139+0{,}085+1{,}083+$$
$$+0{,}096+0{,}106+0{,}005+0{,}001+0{,}064+0{,}011)=2{,}098\cdot 10^{-5}. \quad (3.19)$$

Waiver time:

$$T_0=\frac{1}{\lambda}=\frac{1}{2{,}098\cdot 10^{-5}}=4{,}766\cdot 10^{4}\text{ or }47660(h). \quad (3.20)$$

Probability of trouble-free operation:

$$P(t)=e^{-\lambda\cdot t}=e^{-2{,}098\cdot 10^{-5}\cdot t}; \quad (3.21)$$

P(0) = 1; (3.22)
P(1000) = 0,979; (3.23)
P(10000) = 0,811; (3.24)
P(20000) = 0,673; (3.25)
P(30000) = 0,533. (3.26)

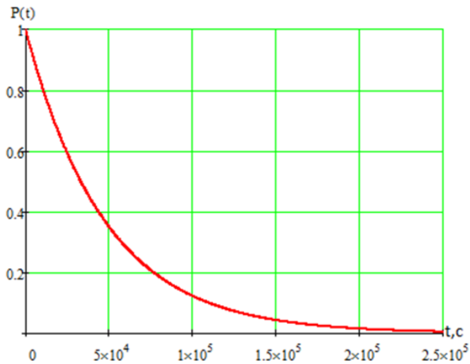

Figure 3.2 – Probability of uptime

The probability of failure is determined by the formula:

$$Q(t) = 1 - P(t) = 1 - e^{-\lambda \cdot t} = 1 - e^{-2{,}098 \cdot 10^{-5} \cdot t}; \qquad (3.27)$$

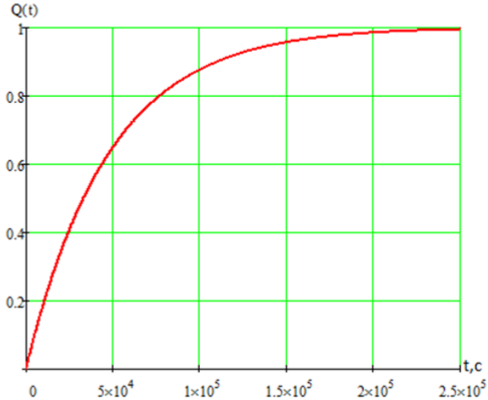

Figure 3.3 – The probability of failure

Let us depict the probability of failure-free operation and the probability of working on a single graph.

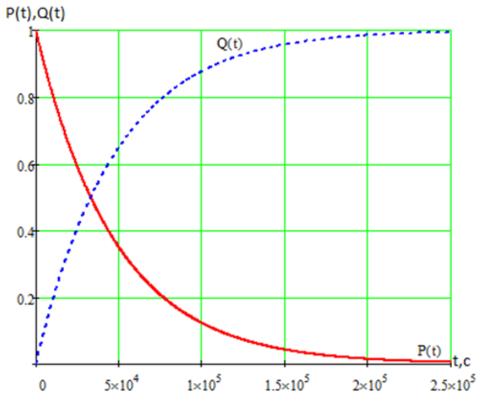

Figure 3.4 – Probability of failure-free operation and probability of failure

3.4 Practical implementation

In the conditions of the aviation-technical base of the Kremenchug Flight College of KhNUIA the practical implementation of the proposed technical solution was carried out (Fig. 3.5 – 3.8).


Figure 3.5 – Arrangement of display devices on devices


Figure 3.6 – EARTH warning indication


Figure 3.7 – "DANGEROUS EARTH" emergency indication

Figure 3.8 – DANGEROUS EARTH warning indication

CHAPTER 4
MODERNIZATION OF INDICATION OF THE SYSTEM FOR PREVENTING COLLISIONS IN THE AIR FOR AIRCRAFT OF LIGHT-ENGINE AVIATION

4.1 General information and problems of use

At the current stage of aviation development and the increase in air transportation and aviation work, more and more attention is being paid to increasing flight safety. The main factors determining flight safety are [74]:

– flight operation of aircraft;
– technical condition of aviation equipment;
– the influence of adverse environmental factors;
– quality of air traffic services.

Air traffic safety is one of the key comprehensive indicators of flight safety, including a combination of components, each of which determines one of its sides.

When organizing air traffic, along with other measures, a system is provided to ensure the safe separation of aircraft in order to prevent collisions in the air. To ensure the safe dispersal of aircraft in space, standards have been developed for vertical, longitudinal and lateral separation.

Based on the needs of air traffic, the ATS unit will inevitably address issues related to aircraft flight. There are simply no other ways to prevent collisions between aircraft, other than maneuvering with speed, altitude, heading, etc. But this forced intrusion into the sphere of activity of the commander controlling the flight of the aircraft is reliably neutralized by his right to request and obtain a new permit if, in the commander's opinion, the permission obtained does not correspond to the safety of the aircraft. The right to make a final decision on matters related to aircraft control remains with its commander. The permission issued by the dispatcher, as already noted, is only related to air traffic and does not relieve the aircraft commander of the obligation not to violate any flight rules established in the interest of safety or for any other purpose [75].

To prevent dangerous proximity of aircraft in the air, radar control of airspace is used. In this case, the airspace is controllable, these include control region (CTA) and control areas (CTR). In these areas, dispatching services are provided, which provides for the monitoring of maintaining safe intervals and distances under the supervision of an air traffic controller. In this case, the crew performs maneuvers with maintaining the heading and level, prescribed by the teams of the air traffic controller [76].

Analyzing the preconditions for a flight accident and aircraft accidents, it turned out that the cause of dangerous proximity and collisions of aircraft in the air, in most cases, is the human factor, the air traffic controller's assessment and prediction is not correct. In this regard, an auxiliary technical system for preventing collisions in the air was developed. The on-board equipment of the warning system is called the TCAS (Traffic alert and Collision Avoidance System). According to ICAO standards, the TCAS system must be installed on all aircraft heavier than 5.7 tons or certified for the transport of more than 19 passengers, and in accordance with Amendment No. 2010-03 of the Eurocontrol, starting from 01.01.2015, all aircraft (version 7.1) [5, 9].

The most applicable at present, on-board equipment of the TCAS II system (modifications 7.0 and 7.1), corresponds to ACAS II level.

Airborne Collision Avoidance System (ACAS) is an airborne collision avoidance system designed to prevent collisions or dangerous airborne encounters by providing pilots with recommendations for maneuvers when a collision risk is detected. The most applicable at present, on-board equipment of the TCAS II system (modifications 7.0 and 7.1), corresponds to ACAS II level. A system that meets these requirements is the TCAS 2000 system. This system is an autonomous on-board collision avoidance system designed to assist flight crews in preventing collisions in mid-air. TCAS 2000 must be enabled during flight in those areas airspace where TCAS is required. The TCAS 2000 system in its basic configuration consists of antennas installed on the aircraft, a TCAS 2000 calculator unit, a Mode-S transponder, and indicators and a control panel installed in the cockpit. The TCAS 2000 (CU) system's computing unit receives data from the aircraft's corresponding devices about the radio altitude, barometric altitude, the aircraft's presence in the air or on the ground, as well as the landing gear retracted or retracted, as well as from the height alarms / control unit or mode control panel (as an option ARINC 429). Nearby aircraft are detected by response signals from the A / C and S mode airborne transponders. The mutual spatial position of the airplanes is estimated, the air traffic is predicted, airplanes that pose a potential collision threat are identified, and the crew is given appropriate instructions (recommendations) displayed on the indicator (Fig. 4.1), as well as voice messages [77].

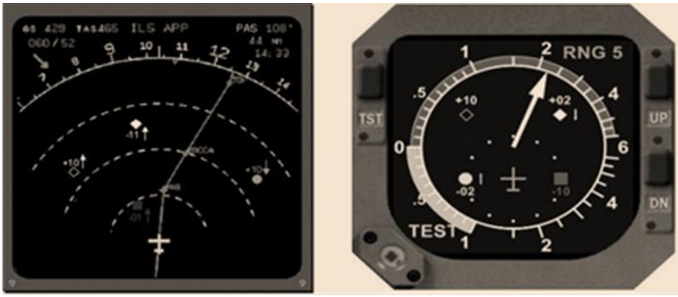

Figure 4.1 – Image of intruder aircraft on ACAS indicators

ACAS equipment can issue two types of recommendations:

1. TA (traffic advisory) – advisory information that a particular intruder is a potential threat.
2. RA (resolution advisory) – recommendations for resolving (eliminating) the threat of collision, which prescribe appropriate maneuvers.

There are three types of ACAS [78]:

– ACAS I provides only TA advisory information (at the ICAO level, international implementation is not planned);

– ACAS II provides TA and RA recommendations in a vertical plane;

– ACAS III provides TA and RA recommendations in the vertical and horizontal planes, but due to the difficult technical implementation of the work on this system, it has been stopped.

The TCAS II algorithm for issuing TA and RA recommendations consists of the steps [79]:

1) determination (assessment) of the mutual spatial position of the aircraft (one's own and the violator);
2) calculating the speed of mutual rapprochement;
3) calculating the flight time τ_{CPA} until the moment of closest approach (CPA - Closest Point of Approach);
4) comparing the calculated τ_{CPA} value with the threshold value τ_{tv} (tau "threshold value").

To assess the relative spatial position of aircraft, TCAS determines three parameters: relative altitude, range, and relative bearing (Fig. 4.2).

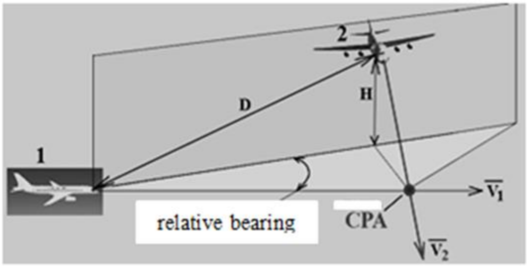

Figure 4.2 – Mutual spatial position of conflicting aircraft

The speed of mutual rapprochement is determined by two components:

1) the speed of reducing the distance between the aircraft;
2) speed reduction height.

The first component calculates the flight time τ_{CPA} in range. Flight time is determined by dividing the distance D by the rate of decrease in range.

The TCAS II system provides TA or RA recommendations provided that both τ_{CPA} and τ_H are less than the threshold τ_{tv}. The threshold value τ_{tv} for the issuance of the recommendation of RA is set in the range from 15 to 35s, and the TA is usually issued for 5 and 20s before the issuance of RA [71]. The specific value of time τпз depends on the sensitivity level SL (Sensitivity Level). The sensitivity level depends on the absolute flight altitude of your aircraft and varies from 1 to 7. The sensitivity level is set automatically either by the TCAS system itself, or by commands from the ground SSR, or by the pilot himself (only levels 1 and 2). The higher the sensitivity level, the larger the sizes of the TA and RA recommendations zones (the higher the level of protection provided).

Figure 4.3 shows the sizes of the areas for issuing TA and RA recommendations depending on the flight altitude of the aircraft or depending on the SL level. The sizes of the zones are indicated in units of time for the threshold value τ_{tv}, as well as in units of distance for the case of a low rate of change of distance. The minimum altitude ZH intervals are indicated on the right (for areas of issuing TA and RA recommendations for height).

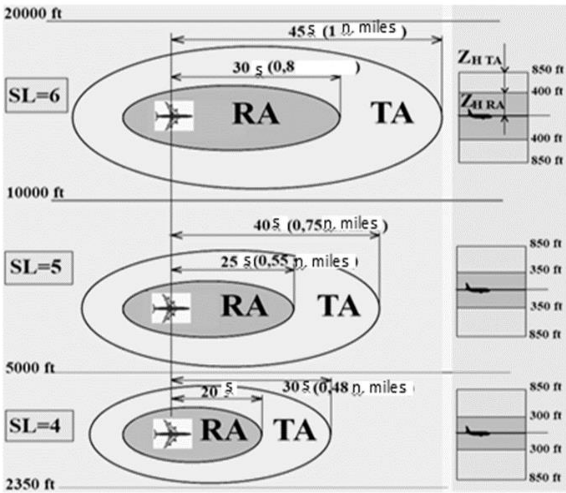

Figure 4.3 – Dimensions of TA and RA recommendation areas depending on SL sensitivity levels.

If the intruder is equipped with the same TCAS II system, requests are sent between the systems via the Mode S data channel to form coordinated RA recommendations. These requests (interrogation signals) are repeated with the maximum number of attempts until the mode S transponder on the intruder aircraft issues a coordination response signal (that it has received the interrogation signal with the RA recommendation and its aircraft will respond in accordance with the received RA recommendation) If the message is not received, the TCAS system independently selects the RA based on the geometric characteristics of the conflict situation.

The TCAS II system includes (Fig. 4.4) [80]:

– TCAS transceiver (computer);

– displays or indicators;

– two antennas (directional – upper and non-directional – lower);

– Mode S transponder (with one or two omnidirectional antennas);

– Remote Control.

The Mode S transponder is an essential element of the TCAS II system, since it is through the transponders that the system receives height information.

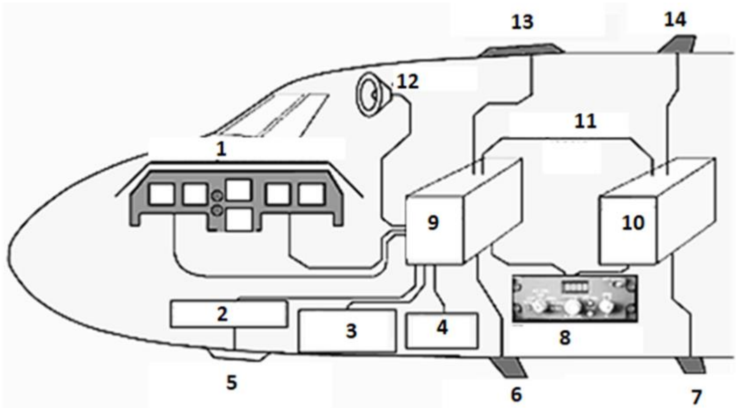

Figure 4.4 TCAS II system equipment: 1 – EFIS or TCAS indicator; 2 – radio altimeter; 3 – air signal system; 4 – landing gear; 5 – radio altimeter antenna; 6 – bottom TCAS antenna; 7 – S transponder antenna; 8 – TCAS Remote Control; 9 – TCAS transceiver; 10 – S transponder; 11 – coordination and prohibition; 12 – sound alert; 13 – directional TCAS antenna; 14 – S transponder antenna.

The TCAS II system is interfaced with on-board systems [81]:

– calculator of air signals to obtain information about the flight altitude (absolute barometric), speed (true, instrument, vertical), etc.;

– radio altimeter, to obtain information about the current true flight altitude (when flying at low altitudes);

– an air-to-ground position sensor, to obtain information about the status of the aircraft (in flight / on the ground).

The block diagram of the TCAS II system is shown in Fig. 4.5.

The operation modes of the TCAS II system are controlled from the control panel (PU). Depending on the configuration and type of equipment, the remote control can be either combined type with the control panel of the transponder, or separate.

The transponder A, C, S and the transmitter of the TCAS transceiver receive the information necessary for the functioning of the system (address code – N; geographical coordinates – φ, λ; altitude; speed, etc.).

The TCAS transceiver consists of a transmitter, receiver and computing device [82]:

– the transmitter requests the transponders of neighboring aircraft in modes S and C;

– the receiver receives responses from the defendants;

– the computing device, on the basis of information extracted from the response signals and information obtained as a result of measurements, evaluates the relative spatial position of the aircraft and issues relevant recommendations displayed on the display or VSI / TRA indicator (VSI-pointer of vertical speed, TRA - display of warnings about air situation and recommendations for resolving a conflict situation).

Signal emission and reception are carried out at the frequencies indicated in the figure.

Interrogation signals are received by the transponder antenna чика. The responder, in accordance with the request code, generates a response signal, is filled with information about the absolute height, the address code of the aircraft II, as well as other data if an advanced squitter (112 bits) is used. The generated response signal is emitted by the mode S transponder antenna at a frequency of 1090 MHz.

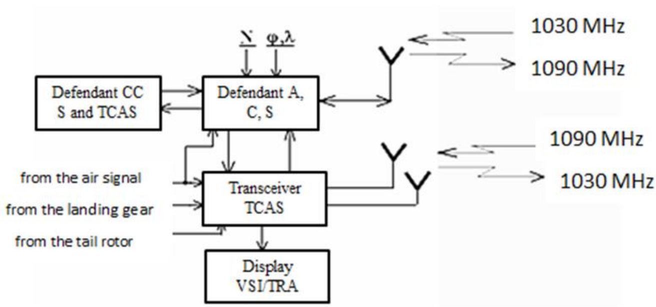

Figure 4.5 – Structural diagram of the TCAS II system

Thus, a response signal containing the altitude and other parameters of the aircraft II is received at the antenna of the transceiver TCAS of the aircraft I.

The aircraft's TCAS transceiver I calculates altitude data, as well as other information, if any. Based on the data on the obtained altitude, a comparison is made of its height with the height of the aircraft II. If it is concluded that the height of the aircraft II is close to the height of its aircraft, then an address request is made for the aircraft II to determine its distance and azimuthal position. Depending on the relative height (and distance), interrogation signals are emitted at intervals of 10 s or about one second. The request / response channels are the same: 2 - 2 - 3 - 3. The distance to the aircraft II is determined by the time interval between the request and response signals, and the azimuthal position is determined by the signal parameters determined by the upper directional antenna [83].

Measurements are taken for each request / response cycle. The rate of change in flight altitude and the rate of change in distance to another aircraft is calculated from several measurements. Measurement data is entered into a collision avoidance logic program to determine if TA or RA is required.

Using a Mode S data link, the TCAS system can transmit RA information with ground SSR Mode S. RA notification is maintained for 18 ± 1 s [84].

The direction of arrival of radio waves from the transmitter of the intruder is determined using a directional antenna mounted on top of the fuselage of the aircraft.

The antenna consists of four asymmetric radiating elements located on the surface of the aircraft in the form of a square lattice with quarter-wave separation. When pairing the output of elements, for example, 1 and 2, 3 and 4 (Fig. 4.6), a radiation pattern is formed in the form of two eights (phase relationships of voltage are indicated in circles).

Amplitude voltage values:

$$U_{1.2=U_0 \sin \beta}$$

$$U_{3.4=U_0 \sin \beta}$$

where: UO is the amplitude for the maximum of the diagram.

Comparison of the received signals in amplitude and phase allows you to determine the angle of arrival of radio waves or the relative bearing of the intruder.

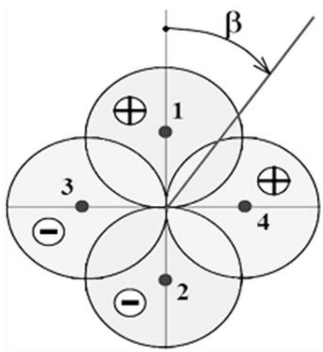

Figure 4.6 – Horizontal radiation pattern of a TCAS directional antenna

In the TCAS system, the directional properties of such an antenna are used in a slightly different way. Reception of signals is carried out only on one element. The pattern of the element has the shape of a circle. If you make alternate switching of elements, for example 1 - 2 - 3 - 4, etc., then a single diagram will scan in the directions "forward-backward-left-right". The bearing is also determined: by comparing the recorded amplitude and phase relationships.

In the vertical plane, the width of the radiation pattern is about 30 °.

In accordance with the requirements of ICAO, the error in determining the relative bearing should not exceed 10 ° [85].

Indicators of the TCAS system can be VSI / TRA indicators (VSI-indicator of vertical speed, TRA-display of air traffic warnings and recommendations for resolving a conflict situation) Fig. 4.7, electronic indicators – displays, as well as modified weather indicators.

Figure 4.7 – Image of the test picture on the display of the VSI / TRA indicator

Table 4.1 – Aircraft symbols on the indicator.

Indicator designation	Danger group / Decryption	Position in the area of recom.	τ tv, s	Range to intruder aircraft, mile
- 12	NOT DANGEROUS / (below 1200)	–	–	More 6
+ 07	CLOSE / (above 700, rise, more than 500)	–	–	Less 6
+ 03	ATTENTION / (above 300)	*TA*	20 - 48	Less 6
+ 02	DANGEROUS / above 200, decrease, more than 500	*RA*	15 - 35	Less 6

Symbols for aircraft designation on the indicator are shown in table1. Depending on the hazard group, the symbols have different colors and shapes. Here, in table1, a description of the designations of the data field is given. The data field includes a two-digit number, a plus or minus sign, and may also include an arrow. A two-digit number indicates the relative height of the intruder in hundreds of feet. If the number is higher than the symbol, then the intruder is higher, and vice versa. In addition, the plus or minus sign also indicates the position of the intruder (above-below). If the data field moves on the screen from a position below the aircraft symbol to a position above it or vice versa, then this means that the intruder crosses the height. The arrow indicates a change in altitude by the intruder aircraft: the up arrow indicates a rise at a speed of more than 500 feet per minute, the down arrow indicates a decrease at a speed of more than 500 feet per minute.

The vertical maneuvers recommended by the TCAS system are indicated by red and green arcs (Fig. 4.8). The red arc shows the pilot which vertical velocity area to avoid. The green arc shows what vertical speed the plane must have in order to avoid a collision.

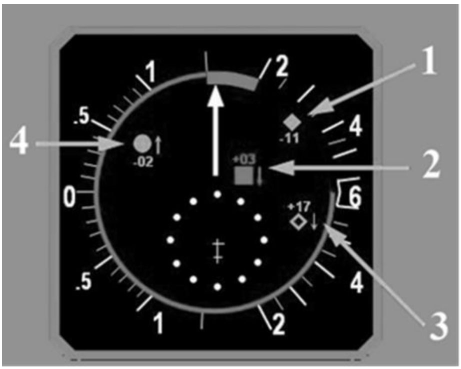

Figure 4.8 – Example of the airborne situation on the VSI / TRA indicator

In this case, the vertical speed of the aircraft must be changed in this way. The order to eliminate a dangerous situation must be executed manually (autopilot is disabled).

The TCAS system for display can use an Electronic Instrument System (EIS). Information from the TCAS system displayed on the screens of electronic indicators of the VSI / TRA type. Applied information is information issued by other sensors of flight and navigation information.

Figure 4.9 shows an example of displaying information from the TCAS system on a flight control indicator (FCI) and on a multifunctional indicator (MFI) [86].

The FCI displays the following information from the TCAS system:

1 – message about the operating mode (in this case STBY) and the status of TCAS;

2 – the border of the vertical review (ABV - N - BLW);

3 – indicator of vertical speed. The RA recommendation is issued as a green arc on the vertical speed scale. The red arc shows the direction and magnitude of unacceptable vertical speeds;

4, 5, 6, 7 symbols of aircraft – violators. Symbols and symbols in the data field are similar to the images on the VSI / TRA type indicators.

At MFI:

1 – RA recommendation is issued as a text message (“DO NOT REDUCE FASTER 10 m / s”);

2 – operating mode message and TCAS status (“TCAS FAIL”);

3 – the border of the vertical review (ABV - N - BLW);

4, 5, 6, 7 symbols of aircraft – violators.

When pairing the TCAS system with the indicators of the weather radar, an image of the air situation can be displayed on their indicators. On the indicator screen of such stations, it is possible to simultaneously display both radar information and information from collision avoidance systems in the air (TCAS), with the ground (TAWS – terrain awareness and warning system), radio navigation information, or separately. In fig. 4.10 shows an example of a combined image of information from the TCAS system and the navigation system on the indicator of the KONTUR radar station [87].

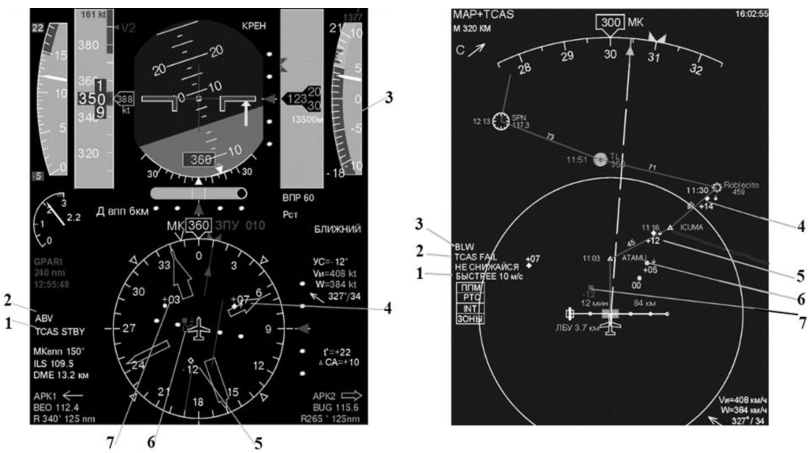

Figure 4.9 – Information from the TCAS system on electronic indicators: a) flight control indicator (FCI); b) multifunctional indicator (MFI)

Figure 4.10 – Image on the indicator of the Kontur radar station.

From the TCAS system, a circle (12 points) and symbols of intruder aircraft with information data fields are displayed on the screen. The image corresponds to the test mode of the TCAS system health check.

From the reviewed review of the airborne collision avoidance system of versions 7.0 and 7.1 of TCAS 2000, we can conclude that this device has complex hardware, which affects the high price of the product, and also has deep integration into the flight and navigation systems of the aircraft, which determines the high cost its installation and maintenance.

Low-powered aviation flights, as a rule, are carried out according to the visual flight rules (VFR), which are carried out at low altitudes, in the daytime and with good visibility. Such flights, as a rule, are carried out in areas of flight information of the lower airspace, in which web-based information services and emergency alerts are provided throughout their territories.

During such a flight, the aircraft is not observed by the dispatcher with the help of radar stations for viewing the airspace. This is because light-engine aircraft fly at low altitudes and also have a small effective reflective radar surface. Therefore, control over maintaining safe intervals and distances between aircraft is assigned to the pilot himself (crew commander), which is carried out visually. By analyzing aircraft accidents involving dangerous proximity, it can be determined that there are cases where visual contact with a conflicting vessel is difficult. This can occur when blinded by sunlight or when a conflicting aircraft is out of the pilot's field of vision.

At the present time, when the number of light-engine aviation, both for special and amateur purposes, is increasing, the number of accidents related to the dangerous approach of aircraft is increasing. Equipping these aircraft with a complete ACAS system, which was discussed above, is not possible due to the high cost of the system itself and the cost of its installation and maintenance.

The problem can be solved by installing a simplified Portable Collision Avoidance System (PCAS) type XRX.

The original PCAS technology was developed by ZAON in 1999. Today, the MRX / XRX line of collision avoidance systems incorporates the fourth generation of PCAS technology. Thanks to these technologies, aircraft equipped with transceivers of the secondary information system are detected in space, with the determination of their distance and altitude.

Traffic information takes three forms [88]:

– the first parameter is the distance, or how far the aircraft is located;

– the second parameter is the relative excess, tells us that how much higher or lower our aircraft is plane;

– the third parameter is the direction of the conflicting aircraft.

In other words, the distance, relative excess, and direction, together can indicate to us the X, Y, and Z coordinates of the threatening aircraft in the three-dimensional space around us, or relative to our position. The detection zone surrounding the aircraft in flight is shown in Fig. 4.11.

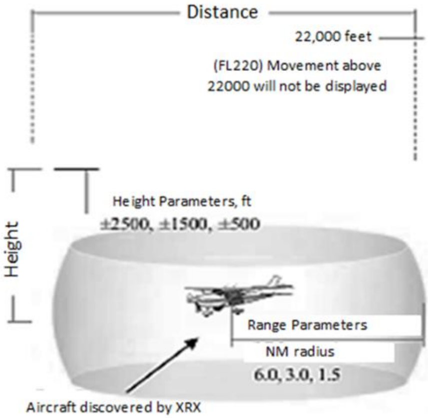

Figure 4.11 – PCAS XRX detection zone.

PCAS XRX presents the following features [89]:

1. Overview of sectors in increments of 45 ° in the "3-D" format.

2. Digital distance scalable from 1 to 6 miles.
3. Relative height, scalable from ± 2500 m to ± 500 feet, with increasing / decreasing value.
4. Air traffic information.
5. Menu-oriented interface, with the ability to select aircraft types and additional calibration parameters.
6. Built-in altimeter, built-in compass, built-in switch-on sensor, internal thermometer – provide the highest possible accuracy in real time.
7. Displays the local responder code, altitude, roll angle, bearing and temperature.
8. Audible voice signals of danger of a warning and advisory nature, both with a Direct ™ headset connected in the cab, as well as RS-232 integrated with other systems.

XRX will display any aircraft equipped with transceivers of the secondary information system that is within the detection zone. The size of the zone is changed by the settings, depending on the air situation. Limitations of both parameters in height and distance can be set, regardless of each other.

The determination of the first parameter – the distance of the conflicting aircraft begins with a request cycle. To start the cycle, a request is sent from ground-based radar stations and / or TCAS, or other active requesting systems in the area of your location. This signal is sent at a frequency of 1030 MHz. As for TCAS, this request distance can have a radius of 40 miles or more, relative to the source sending the request. The distance of ground radar can be 200 miles or more. A transponder on any aircraft in the request area responds at a frequency of 1090 MHz with a transponder code (known as Mode A) and an altitude code (Mode C). Height information is transmitted in encoded format. Transponders operating in Mode S also send a response at the same frequency, and Mode A information (transponder) and Mode C information (altitude) are encoded during mode S transmission. Military aircraft also use the same frequency but a different dispatch protocol. The transponder of our aircraft must also respond. However, PCAS looks for this signal and does not perceive it as an airborne threat. A response from any aircraft within the XRX detection area (maximum 6 miles) will be received. The distance is calculated, the height code is decoded, and the angle of arrival of the signal is determined. PCAS recognizes requests from TCAS, Skywatch, and any other "active" systems, military protocols, and S-mode transmissions. The distance to a conflicting aircraft is determined by the time between its own request signal and the response signal from another aircraft [90].

Determination of the second parameter – the relative height of the conflicting aircraft. The PCAS altimeter is involved in the process of determining this parameter. The algorithm for calculating this parameter is as follows:

1. The decoding device of your transponder transmits your local (current) altitude, determined by the pressure value of the coding altimeter of the airborne signal system.
2. XRX intercepts and decodes your current altitude.
3. The XRX compares this to the height obtained from the built-in barometric altimeter to ensure the proper level of accuracy.
4. If allowed, the XRX uses the transponder height as a reference point.
5. XRX provides accurate relative altitude information for traffic display.

Sometimes, receiving information about the local altitude is not possible from your transponder, or it is impossible to rely on it. This is normal for all collision avoidance systems and the XRX automatically provides a workaround for resolving the problem. In these cases, the following occurs [91]:

1. XRX uses the built-in barometric altimeter as a reference point.
2. XRX provides accurate relative height information for traffic display.

The portable PCAS collision avoidance device, which displays altitude information, should rather rely on a secondary source for determining altitude rather than only information from its own transponder.

The definition of the third parameter – the direction to the conflicting aircraft is the design feature of the antenna. XRX uses a specially designed antenna that uses a combination of the amplitude of the phase neutralization signal, which is the only way to accurately determine the direction directly from inside the pilot's cabin. This array consists of four finely tuned directional antenna elements that are connected to four separate superheterodyne radio frequency receivers. The displayed information about the direction of movement of another aircraft, to adapt course changes, is directly tied to the internal solid-state compass, therefore, the direction that you see at any time is displayed relative to your course. This design allows the device to "hear" from which direction the plane is approaching and display information on the screen. This method allows you to track multiple aircraft at once. The displayed course information is directly related to the angle at which the XRX system is placed on the visor of the dashboard. Target aircraft transponders are not always in transmission mode. Therefore, if the target is directly in front of you and you begin to turn, the device will continue to erroneously indicate that the aircraft is still directly in front of you, until the next transponder transmission. Since XRX has in its composition built-in compass, the device knows that you have changed your course and can accurately recalculate the relative positions of other aircraft. This applies to any aircraft within the detection distance. It is very important that the compass is accurately calibrated to ensure overall accuracy in heading. Without the necessary level of accuracy of the internal compass, the movement will still be displayed right in front of the aircraft, until the next response is received. With a built-in compass, the XRX will correctly and continuously track the movement, constantly updating relative position information, even between transponder responses.

The greatest threat is determined from the number of aircraft within the detection zone you set, by comparing, first of all, vertical separation (± relative height), and, secondly, the distances to aircraft displayed at a given time. PCAS uses proprietary algorithms to determine which of two or more aircraft represents a big threat.

The use of PCAS XRX is possible even on aircraft that are not equipped with a secondary radar transponder, since the XRX equipment includes an integrated altimeter. It is commonly used as a backup source to determine local elevation. Therefore, this equipment can be used on gliders, balloons, or ultralight aircraft, which, as a rule, are not equipped with transceivers. Regardless of the local transceiver, the XRX will always be able to determine the local height, providing accurate air traffic information [92].

Information about motion detection is provided to the crew in visual and audio form. At the same time, gradation of approaching aircraft is made according to the degree of danger. The assessment is carried out according to the following criteria [93]:

the relative excess of the threatening aircraft (vertical separation interval);

the vertical direction of the speed of the threatening aircraft (climb or decrease over time);

the vertical direction of the speed of your aircraft;

distance to the target, if two or more aircraft meet, relative to the above criteria.

As a result, information about three conflicting aircraft is displayed for display, one is the main (most dangerous) and two minor.

The XRX includes two methods of warning of an impending threat: voice messages through a headset, a tone generator loudspeaker, and a brief flash on the display screen to warn you of an impending threat. Two levels of threats are listed: alerts and traffic alerts.

The main unit of the device is the PCAS XRX device (Fig. 4.12).

Figure 4.12 PCAS XRX instrument

XRX is an autonomous, passive system. The PCAS XRX has a built-in antenna for receiving transponders from other aircraft, as well as a built-in electronic compass and an altimeter. The installation of the device consists in its placement, power supply and the output of an audio channel for sound alerts. The preferred location for the XRX is the cab dashboard visor above the instrument panel. To ensure the best sensitivity of the XRX, it is necessary to clean the area around the antenna array from any approximately 6 "obstacles, including a magnetic compass, which must be at least 5" from the XRX to ensure normal calibration. This also applies to the middle windshield pillar, GPS antennas, satellite meteorological antennas (especially those with magnetic base), etc. Compliance with these rules will avoid possible magnetic interference and ensure proper operation of the XRX antenna [94].

A visual indication of the air situation is displayed on the front panel of the PCAS XRX. The device has the following controls and indications (Fig. 4.13).

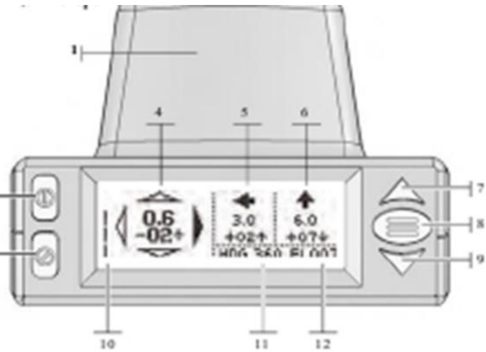

Figure 4.13 Control and indication of PCAS XRX: 1 - Directional antenna; 2 – POWER button; 3 – MUTE button; 4- Indication of the main aircraft; 5 – Indication of minor aircraft No. 1; 6 – Indication of minor aircraft No. 2; 7 – UP button; 8 – Menu call button; 9 – DOWN button; 10 – Sound level indicator.

When a hazard is detected and assessed, information about conflicting aircraft is displayed on the display screen of the air situation (Fig. 4.14). When displaying information about primary and secondary aircraft, the data necessary for the pilot to represent the relative position of these aircraft relative to their own aircraft is displayed.

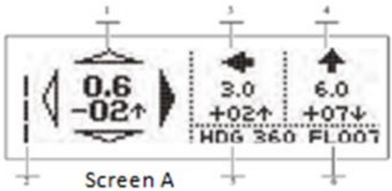

Figure 4.14 – Information display on the PCAS XRX device: 1 – The main aircraft; 2 – Sound level indicator; 3 – Secondary aircraft No. 1; 4 – Secondary aircraft No. 2; 5 – Own course; 6 – Own height.

Providing information about the movement is carried out by indicating the parameters (Fig. 4.15).

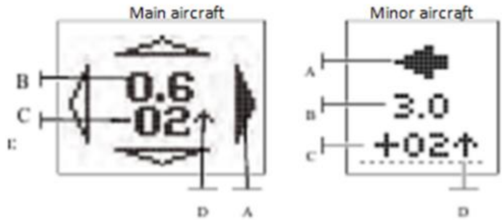

Figure 4.15 – Parameters of traffic information: A – Direction relative to your course (determined by the built-in compass scale); B – The distance to the conflicting aircraft in nautical miles; C – Height relative to your actual height ((+) - higher or (-) - lower); D – Vertical Ascending (∧) or Descending (∨).

Other aspects of displaying the air situation [95]:

– "No movement" is displayed as blank spaces on the display in both the distance and altitude and direction sections. This rule applies to both the primary and secondary traffic areas;

– an aircraft at the same altitude displays "00" in the relative excess section;

– on a secondary position in terms of threat level (1 and 2), the direction of movement can only be displayed in increments of 90 °;

– only the main aircraft in terms of threat level can be displayed in increments of 45 °.

Flights of light-engine aviation are carried out according to the Visual Flight Rules, in which the pilot, having received traffic information, is obliged to establish visual contact with the conflicting aircraft in order to avoid dangerous proximity and collision. Sometimes the information from dispatching services may not be enough, visual detection may be difficult due to visual distortions. Visual distortion may occur for the following reasons [96]:

– even for a well-trained vision, a small aircraft at a distance of 1.5 to 2 kilometers is too small to see it;

– visual phenomena, such as the effect of the underlying surface, optical myopia, and haze can obscure the aircraft;

– only a relatively small "sector" of 360 ° of view around the cockpit is within the scope of the pilot;

– aircraft above, below and behind can be blocked by the hull of your aircraft, which makes it difficult to detect;

– Aircraft at your height or level above are typically 200 feet lower for every half mile of distance between you and the aircraft. This is an optical illusion that is caused by the curvature of the Earth (horizon) combined with the angle of attack of your aircraft.

The task of the PCAS XRX system is to provide the pilot with reliable traffic information in time to make a decision on correcting a conflict situation.

The problem of pilot perception of PCAS XRX indication is:

– the indicator has small geometric dimensions (width - 100 mm, height 69 mm), which makes it difficult to read information;

– an indicator of black and white image and not high brightness, which complicates the perception of information in bright lighting of the cabin with the sun;

– an indicator is placed in the center of the visor of the dashboard, which corresponds to the 7 ergonomic zone of perception of the pilot;

– in the event of a conflict, the pilot focuses on monitoring his own flight parameters (altitude, heading, speed) and shifting attention to the PCAS XRX indicator significantly increases the reaction time.

4.2 System upgrade

To solve the problem, it is proposed to duplicate the visual indication of the PCAS XRX using an additional information display device.

The additional indication device is a ring in size of the analog device of the barometric altimeter (Fig. 4.17). The indicator of this altimeter is located on the dashboard in the first ergonomic zone of the pilot.

Figure 4.17 – Altimeter VD-10K.

The additional indication device is made using 3D printing, in which red and yellow LEDs are built-in (Fig. 4.18).

It is proposed to place the device on the edging of the altimeter. Thus, information about dangerous traffic will be in the zone of the best perception of the pilot, without distracting his attention.

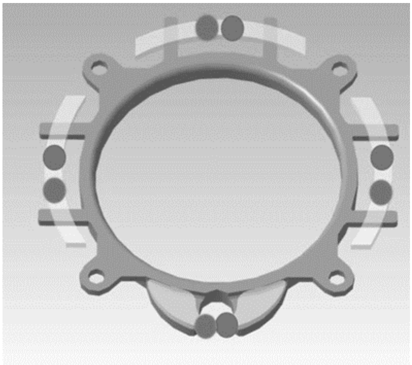

Figure 4.18 – Additional indication device

The LEDs are placed in pairs depending on the direction, respectively, at 00, 03, 06 and 09 hours of the dial. The LEDs light up depending on the air situation around the aircraft and duplicate the information that is generated by the PCAS XRX device. Depending on the gradation of approach of the conflicting aircraft, the LED of the corresponding color lights up on the additional indication device. If the conflicting vessel is identified by the PCAS XRX system as the main one, the red LED; if the additional one, the yellow LED. The location of the triggered LED corresponds to the direction of the conflicting aircraft, relative to its own course.

The algorithm of the signaling principle of the additional indication device and its relationship with the PCAS XRX indication are considered using four traffic options as examples.

Option 1. The main conflicting aircraft approaches from the top left with a decrease, the secondary one on the right (Fig. 4.19).

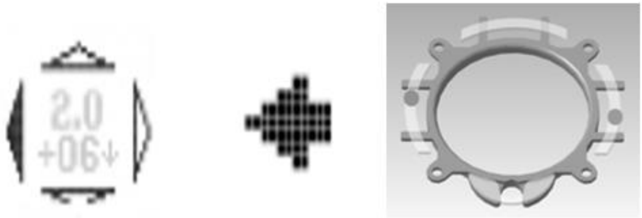

Figure 4.19 – Indication of option 1.

Option 2. The main conflicting aircraft approaches in the opposite direction, the secondary one in the rear (Fig. 4.20).

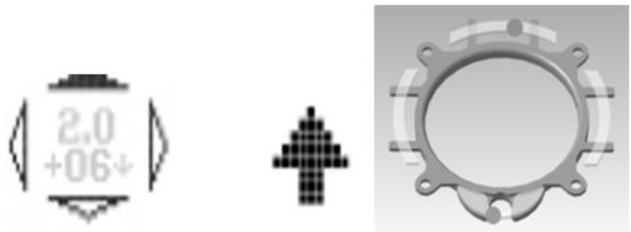

Figure 4.20 – Indication of option 2.

Option 3. The main conflicting aircraft approaches from the top right with a decrease, the secondary - from the left (Fig. 4.21).

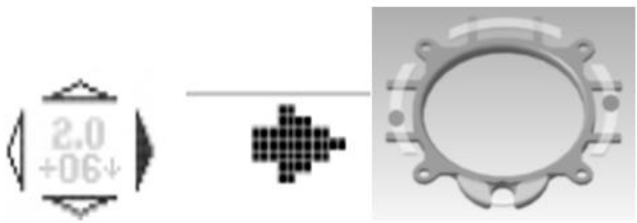

Figure 4.21 – Indication of option 3.

Option 4. The main conflicting aircraft approaches from behind from above with a decrease, the secondary - in the opposite direction (Fig. 4.22).

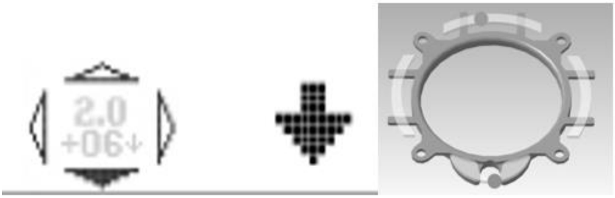

Figure 4.22 – Indication of option 4

According to the TCAS II collision avoidance concept, conflicting aircraft should be diverged by a change in altitude, the onboard ACAS will give crew information on climb or descent with prescribed intensity. Accordingly, during the visual flight of a light-engine aircraft, the pilot will also get out of the conflict by changing the height. It is easy to assume that in case of a dangerous approach, the pilot's attention will be focused on the review of the air space in the front hemisphere and on the altimeter indicator. The PCAS XRX indicator, which is located in the seventh ergonomic zone, will distract the pilot's attention, which will increase the reaction time to a dangerous approach.

When using the proposed additional indication device, the pilot will directly observe his current altitude, direction of the approaching aircraft and the degree of danger. In the event of an alarm, the pilot's task will be reduced to visual detection of a conflicting aircraft, while visual illusions are possible (as described above), and maneuvering in height until the red signaling devices of the device go out. If there are yellow luminous annunciators, the pilot monitors the altitude keeping by the altimeter indicator and the space in front of the aircraft without scattering attention. Information from the PCAS XRX indicator can be read occasionally to control the distance to the conflicting aircraft and change the relative altitude. Based on this, the additional indication device allows to improve the pilot's perception, thereby reducing the decision-making time while avoiding a conflict situation and improving air traffic safety.

The additional indication device will be connected to the PCAS XRX through the electronic unit to the RS-232 connector of the device. This connector is used to connect the XRX instrument to a wide distance of third-party systems, namely to moving maps and electronic flight information systems, including Garmin GPSMap 396/496, AnywhereMap, Blue Mountain Avionics, Grand Rapids Technologies [72].

The electronic unit is used to convert video information from the XRX device into a signal for connecting the corresponding LED of the additional indication device. The switching block diagram is shown in Fig. 4.23.

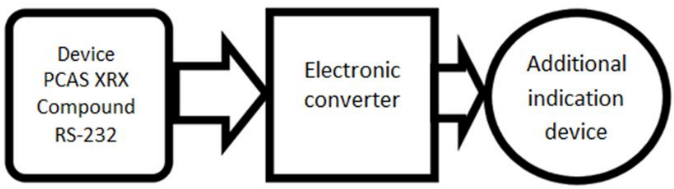

Figure 4.23 – Block diagram of the switching device for additional indication.

Since PCAS XRX is not subject to FAA certification and is an auxiliary tool, and the additional indication device itself does not impair the pilot's perception of altitude information from the barometric altimeter pointer, the commissioning of this indicator will not cause legal conflict.

Application of the developed device for additional indication will allow:

– display an alarm about dangerous proximity in the 1 ergonomic zone of perception of the pilot (zone of placement of the barometric altimeter);

– improve the perception of information by the pilot with vibration and visual illusions;

– reduce the time a pilot makes a decision to resolve a conflict situation;

– increase flight safety.

Further work on the proposed device will be as follows:

– calculation of the necessary brightness and selection of LEDs;

– development of an electronic converter for interfacing the device with the PCAS XRX device.

CHAPTER 5
COMPLEX OF UNMANNED AERIAL VEHICLES POWER SUPPLY USING ALTERNATIVE ENERGY SOURCES

5.1 Review of the current state of development of power systems for unmanned aerial vehicles

Ukraine possesses a full cycle of aviation engineering and occupies a significant place in the global aviation market in the transport and regional passenger aircraft sector, which allows the development and production of aviation technology in areas such as aircraft engineering, on-board radio equipment, focused on the use of satellite communication systems, navigation and observation, ultralight and light aircraft, helicopter construction, unmanned aerial vehicles. Unmanned aerial vehicles (UAVs) are no exception. Today, this technology is applied in many areas of activity and has extremely high prospects for other areas. Unmanned aerial vehicles (UAVs) are currently used to address a wide distance of tasks, such as border patrols, reconnaissance, transportation and armed attacks. This diversity is due to the fact that UAVs are very technological, which explains their widespread use. Modern technologies of UAV energy supply have not yet reached the proper level, due to the dynamic development of this technology. Therefore, the purpose of the work is to develop a variant of the power supply system of the UAV using, in addition, alternative power sources and control system of the proposed grid.

The main components of the UAV are: an airplane with a special landing system, a power plant, a power supply for it, a power supply system, on-board radio electronic equipment (on-board control equipment and electronic elements of the target load). The UAV scheme in NATO countries is presented in Figure 5.1.

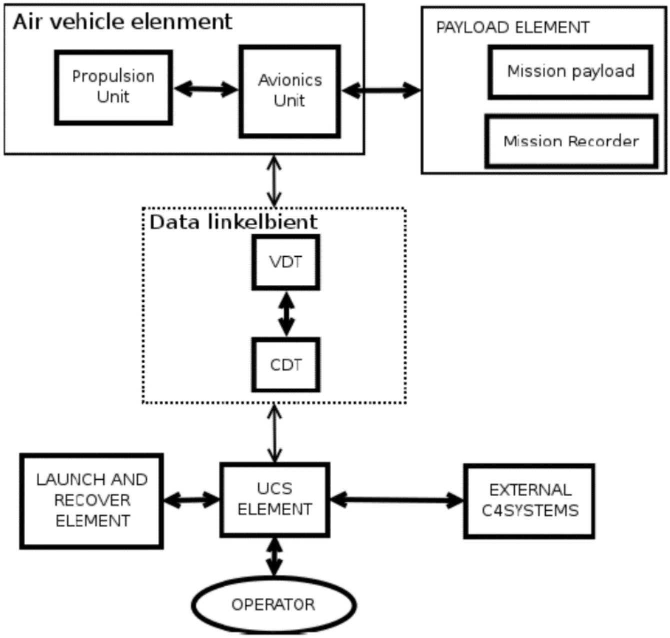

Figure 5.1 – Energy supply system for unmanned aerial vehicles

The UAV should consist of three main elements: air vehicle element, payload element and control system (UAV air component). To analyze the possibility of external influence it is expedient to consider elements that can interact with other components using a wireless communication line (radio, optical, acoustic). In this case it may be a control system and a target load.

UAVs are characterized by the following advantages over manned aeronautics, such as: the lack of a need for crew and systems for its life support, in aerodromes; relatively low cost and low costs for their creation, production and operation; relatively small weight and dimensions in combination with high reliability, significant length and distance of flight, maneuverability and a list of target equipment that can be placed on board, etc [63].

The type of control system determines the type of UAV.

Remotely manned aircraft are guided directly by the operator within the visibility through the ground station. They are equipped with a digital data channel that can be transmitted to the ground in real-time through direct line of sight or through a satellite channel up to 50 Mb/s.

Remotely controled operate autonomously, but can be driven by a pilot that uses only feedback through other control subsystems. Such aircraft include analog and digital channels, the first one providing a stable transmission of information up to 40 km and the other one up to 15 km.

Automatic aircraft perform pre-programmed actions. At UAVs of this type there are integrated systems of automatic piloting with GPS receivers, gyroscopes, accelerometers, various sensors, which allows working in real time and transmitting data through a communication channel with a frequency of 1 MHz Remotely controlled aviation systems are controlled by embedded systems, such as the UAS Analyzer.

Consider a more detailed control system; the scheme is presented in Fig. 5.2.

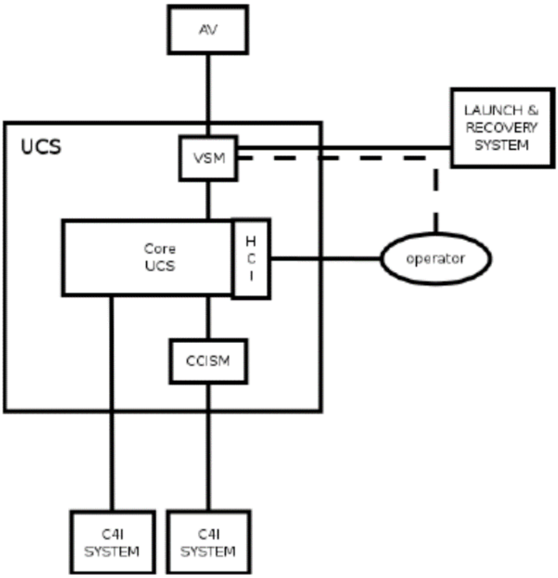

Figure 5.2 – Power control system of unmanned aerial vehicles

The unmanned aerial vehicle control system has the following functional architecture [71]:

– engine, maneuvering and flying support (air vehicle / AV);
– operation controller for AV (VSM);
– operator interface (HCI);
– core (core USC);
– launch and recovery system;
– agrees target load unit (CCISM);

– external connecting c4I systems can be target load (c4I system).

The height of the flight significantly affects the work of the whole complex of electrical equipment and other airborne equipment of the aircraft.

External influences on electrical installations can lead to various types of damage, for example, to breakage of wires and windings, especially in the places where they are soldered, until cracks and damage to electrical insulating materials, accelerated wear of the axes and bearings in actuators, deviations from normal operation of spring and moving elements of mechanical systems.

The tactical and technical requirements for aircraft equipment, developed taking into account the conditions of operation of the electrical equipment and its purpose, include the following indicators: reliability and faultiness, requirements for mass and dimensions, strength of electrical equipment, chemical resistance of electrical equipment, ease of operation and repair of electrical equipment, economic requirements.

From the onboard generators all the electronics are emitted on board the aircraft, so the failure of generators will lead to the discharging of all on-board equipment. In this case, in some types of aircraft, manufacturers install retractable wind power units (RWPUs) that produce current due to the fact that the wind wheel is spinning under the influence of the counterflow of air on the blade, which makes it possible at least to keep track of critical technical indicators of the state of airborne equipment and aircraft systems.

At present, solar batteries (SBs) are one of the most promising alternative sources of electric energy in aircraft. Taking into account the fact that the SBs have been used in cosmonautics, which occupy a dominant position among other sources of autonomous power supply, we can talk about the further active their implementation in the system of primary emergency power supply aircraft systems, as additional sources of electrical energy [72].

Therefore, in view of the urgency of the problem of increasing the reliability of the operation of the entire complex of aircraft equipment, in order to increase the safety of operation, it is expedient to consider the issues of modernization of the airborne power supply aircraft, including renewable energy sources.

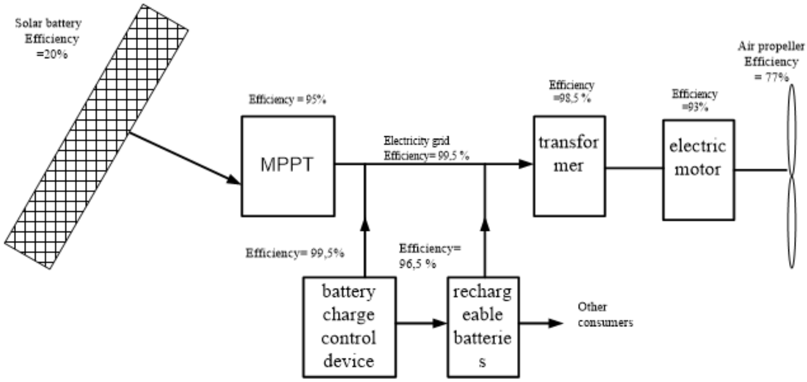

Figure 5.3 – Principle diagram of power plant for unmanned aerial vehicles using solar energy

5.2 Development of energy supply system for unmanned aerial vehicles using alternative energy sources

Taking into account the features of modern aircraft, the authors recommend the structure of the power supply system of the aircraft (Fig. 5.3), which contains: RES1 and RES2 – renewable energy sources, BP – battery pack, BMU – battery monitoring unit, CS – control system, EMC1 and EMC2 – electromechanical complexes of the power system of electric motors based on asynchronous motors with short-circuited rotor (AMSCR), G1 and G2 – generators, E1 and E2 – aviation engines of internal combustion.

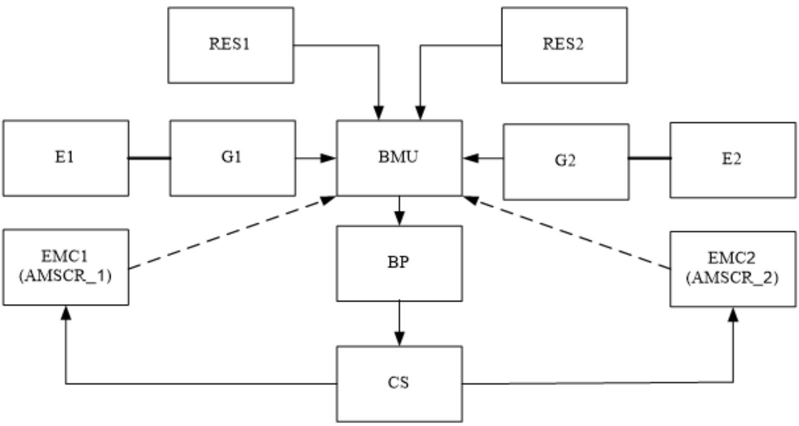

Figure 5.4 – Recommended structure of the aircraft power supply system

In modern aircraft, the structure of the power supply is built in such a way that the main sources of electric energy (EE) are generators, whose work is directly connected with the operation of the internal combustion engines (aircraft engines). In case of failure of internal combustion engines, aircraft in-flight power system is powered solely from the batteries, which is the emergency source EE onboard. Meanwhile, the emergency power supply system on the basis of batteries designed to supply electro starter and equipment ignition when starting the aircraft engines, it is vitally important to consumers during the flight. The lifetime is an important characteristic for battery and depends on many internal and external factors [8]. Complicated specific operating conditions dictate the necessity of monitoring the status of aircraft on-board batteries. The authors propose to implement condition monitoring on-board batteries in the BMU unit (see Fig.5.4). Meanwhile, the unit BMU battery will perform the functions of the charger. It is also proposed in addition to aircraft engines, is standard on the aircraft, in parallel to set the motors and as an additional source of the primary side of the power supply system, renewable energy sources. Given the basic tendencies of development of aircraft in the world today, among the major indicators of the Autonomous aircraft power systems is their energy efficiency, reliability and manageability. Thus, we will consider each indicator separately. The main factors that shape the features of the application of additional electrical power sources of low power onboard include minimizing weight and size characteristics and the need for interim energy storage with a specialized charge-discharge controller. The recommended option of the aircraft power supply system (Fig. 5.5) the battery pack has a capacity sufficient to supply in an emergency situation during the flight is not only responsible consumers (controls and navigation), but also the supply of electromechanical complexes power system motors (EM).

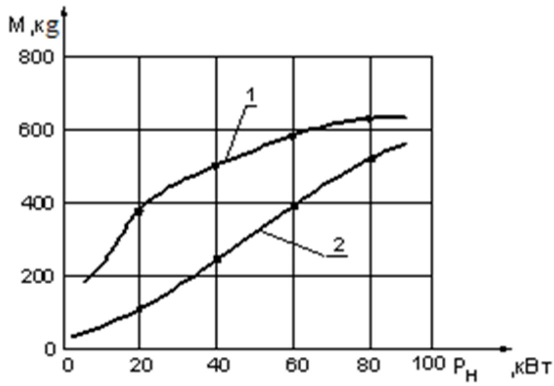

Figure 5.5 – Dependence of the mass of asynchronous and synchronous generators on power: 1 – synchronous generator, 2 – asynchronous generator with short-circuit rotor

Although in the generator mode, the short-circuit induction motor (AMSCR) is rarely used due to the presence of an external cool-down characteristic and imperfect condenser excitation, but such application has a number of undeniable advantages over synchronous generators [5] such as: simplicity and reliability of the design; small weight and dimensions; low cost; easy installation and maintenance.

Taking into account the possibility of EE, including AMSCR, to work both in power and in generator mode, and optimum weight and weight indices, AMSCR is the optimal option for the implementation of additional power sources of low power on board the aircraft.

The energy efficiency of the on-board power supply system can be expressed as the ratio of the difference between the energy produced W_{ps} and the energy losses in the converters ΔW_p and rechargeable batteries ΔW_b:

$$k_e = (W_{ps} - \Delta W_p - \Delta W_b) / W_{ps\_max} . \quad (5.1)$$

From the analysis of formula (2.1) it can be seen that the energy efficiency of the airborne power supply complex-electric power consumption of the aircraft depends on its structure and the coefficients of the usefulness of the transforming devices. An integrated approach to building a power supply system-power consumption of the aircraft will reduce losses in the distribution board network [9-10].

Next we will consider the reliability index, which is closely related to the reservation. Since in case of general reservation, the failure of the on-board electrical equipment of the aircraft will come with the refusal of all backup and one main, then with a separate reservation and in the presence of backup chains probability of failure of aircraft on-board electrical equipment will be equal to the product of the probability of failure of the main $Q_{осн}$ and backup $Q_{резі}$ chains:

$$Q(t) = Q_{осн}(t)\prod_{i=1}^{m} Q_{резі}(t) = \prod_{i=1}^{m+1} Q_i(t) \quad . \tag{5.2}$$

In the case of a separate reservation, if each main element has m backup elements, the probability of failure of the on-board electrical equipment of the aircraft due to the failure of elements of the i-th type is equal to the product of the probabilities of failures of the i-th element q_i and all its reserving elements, i.e.:

$$Q_i(t) = \prod_{i=1}^{m+1} q_i = \prod_{i=1}^{m+1}(1 - p_i(t)) \quad , \tag{5.3}$$

Where $p_i(t)$ is the probability of failure-free operation of the i-th element and all its reserve ones:

$$p_i^{'}(t) = 1 - \prod_{i=1}^{m+1}(1 - p_i(t)) \quad . \tag{5.4}$$

As can be seen from formulas (5.2–5.4), when connecting additional power sources to the on-board power supply system of the aircraft using backup chains, the probability of the failure of on-board electrical equipment will decrease, which will increase the reliability of the electrical supply system of the onboard assembly.

Moreover, the probability of failure-free operation of the power supply system of the airborne complex in the general reservation was 0.98, and in the scheme of the previous connection 0.85.

The modern concept of aircraft development sets forth the requirements related to the miniaturization of on-board power and electronics systems, as well as requirements for the use of advanced technologies for manufacturing aircraft designs. Given the application of nanotechnology in the production of SB, there is a prospect of increasing the efficiency of their functioning and at the same time, a significant reduction in their cost. The implementation, if possible, of such implementation (depending on the design of the aircraft) as additional sources of the main electrical power supply system, the retractable wind power installations and the use as power systems of electric motors to install asynchronous motors with a short-circuited rotor, with the possibility of their use in generator mode, is also relevant.

5.3 System for managing power supply of unmanned aerial vehicles using alternative energy sources

Based on the tree of the logical conclusion of constructive and technological factors, we model the structure of the hierarchical neuro-fuzzy network (Fig. 5.6).

Each element of this structure represents a certain level of the logical tree of influence on the system of power supply of an unmanned aerial vehicle during operation. Each element has a term-set of expert estimates, which is indicated on the input of parameters on the line: "L - low", "BA - below average", "A - average", "AA-above average"; "H - high" [59].

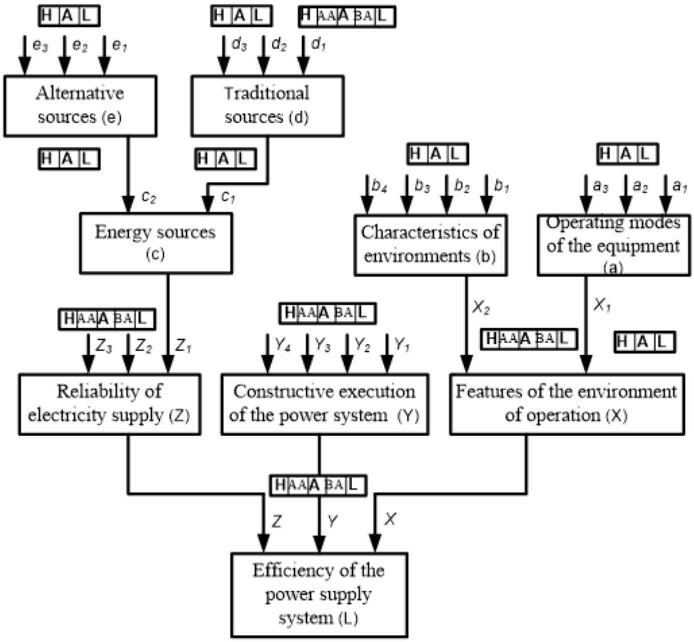

Figure 5.6 – Structure of a hierarchical neuro-fuzzy network to determine the effective system of power supply to an unmanned aerial vehicle

Influence factors influencing the efficiency of power supply of an unmanned aerial vehicle are shown

$$L = f_L (X, Y, Z), \tag{5.5}$$

$$X = f_X (x_1, x_2), \tag{5.6}$$

$$Y = f_Y(y_1, y_2, y_3, y_4), \quad (5.7)$$

$$Z = f_z(z_1, z_2, z_3), \quad (5.8)$$

$$x_1 = f_{x1}(a_1, a_2, a_3), \quad (5.9)$$

$$x_2 = f_{x2}(b_1, b_2, b_3, b_4), \quad (5.10)$$

$$z_1 = f_{z1}(c_1, c_2), \quad (5.11)$$

$$c_1 = f_{c1}(d_1, d_2, d_3), \quad (5.12)$$

$$c_2 = f_{c2}(e_1, e_2, e_3, e_4), \quad (5.13)$$

where X is a linguistic variable describing the specifics of the environment of exploitation; Y – a linguistic variable describing the influence of the constructive execution of the power supply system; Z – a linguistic variable describing the reliability of power supply; x_1 – operating mode of the equipment; x_2 – characteristics of the environment; y_1 – weight of the equipment; y_2 – peculiarities of fastening of equipment; y_3 – volume of equipment; z_1 – energy source; z_2 – battery charge level; z_3 – electric supply system; a_1 – standard operating mode of the equipment; a_2 – failure of the traditional system of electrorazing; a_3 – power from batteries; b_1 – density; b_2 – insolation; b_3 – cloudiness b_4 – wind speed; c_1 – traditional energy sources; c_2 – non-traditional energy sources; d_1 – generator 1; d_2 – generator 2; d_3 – battery; e_1 – low-potential energy; e_2 – solar energy; e_3 – wind energy.

Based on the logical conclusion tree of the constructive and technological factors of influence on the aircraft power supply system [4] and the structure of the hierarchical neuron-fuzzy network, we will make an assessment of the levels of linguistic variables.

The following system of fuzzy logic equations corresponds to the linguistic statement describing the influence of different parameters of energy alternative sources on the efficiency of the aircraft power supply system (Table 5.1):

$$\mu_H(e) = \mu_H(e_1) \wedge \mu_H(e_2) \wedge \mu_H(e_3) \vee \mu_H(e_1) \wedge \mu_H(e_2) \wedge \mu_H(e_3) \vee \mu_H(e_1) \wedge \mu_H(e_2) \wedge \mu_C(e_3),$$
$$\mu_C(e) = \mu_C(e_1) \wedge \mu_C(e_2) \wedge \mu_H(e_3) \vee \mu_H(e_1) \wedge \mu_C(e_2) \wedge \mu_E(e_3) \vee \mu_C(e_1) \wedge$$
$$\wedge \mu_H(e_2) \wedge \mu_E(e_3) \vee \mu_C(e_1) \wedge \mu_C(e_2) \wedge \mu_H(e_3) \vee \mu_H(e_1) \wedge \mu_E(e_2) \wedge \mu_C(e_3) \vee \mu_E(e_1) \wedge \quad (5.14)$$

$$\wedge \mu_{H}(e_2) \wedge \mu_C(e_3) \vee \mu_C(e_1) \wedge \mu_C(e_2) \wedge \mu_E(e_3), \quad (5.15)$$

$$\mu_2(e) = \mu_E(e_1) \wedge \mu_C(e_2) \wedge \mu_E(e_3) \vee \mu_E(e_1) \wedge \mu_C(e_1) \wedge \mu_C(e_3) \vee \mu_E(e_1) \wedge \mu_E(e_2) \wedge \mu_E(e_3). \quad (5.16)$$

Table 5.1 – Fuzzy matrix of knowledge about the relation on the system level

	IF		THEN
Low potential energy (e_1)	Solar energy (e_2)	Wind energy (e_3)	Effect of alternating energy sources (e)
Low	Low	Low	Low
Low	Medium	Low	
Low	Low	Medium	
Medium	Medium	Low	Medium
Low	Medium	High	
Medium	Low	High	
Medium	Medium	Medium	
Low	High	Medium	
High	Low	Medium	
Medium	Medium	High	
High	Medium	High	High
High	High	Medium	
High	High	High	

The technique of fuzzy logical conclusion, which was applied to the information in the previous stages, allows calculating indicators that are predicted as fuzzy sets. Fuzzy sets determine the degree of fermentation efficiency when choosing an alternative energy source for a fixed vector of influence factors. To move from fuzzy sets to quantification, you need to complete the dephasing process. Among the various methods of dephasing we will use the method "Centroid" [1]. We carry out defazification at the level of alternative energy sources for the temperature stabilization of anaerobic fermentation the value of the membership functions of pair comparisons is calculated, and we will use the Saati scale for the expert evaluation of the elements [2].

The matrix of pair comparisons of various alternative energy sources, in terms of their proximity to the term "low", is given in Table 5.2. The factor e - alternative energy sources is defined on the universal set U (e) = {1, 2, 3} (o.y.). The linguistic values of this factor are given by the term-set T (e) = <low, medium, high> [5].

Table 5.2 – Paired comparisons of non-traditional energy sources according to their proximity to the term "low"

		e_1	e_2	e_3
$Alow(e) =$	e_1	1	6 / 9	1 / 9
	e_2	9 / 6	1	1 / 6
	e_3	9	6	1

In the formation of this matrix expertly determined only the third row and the elements of other lines were calculated, based on the properties of the resulting matrix [2].

According to the data of the table 5.2 the degree of membership of the elements e_1, e_2, e_3 is obtained, to the term "low":

$$e_{low}(e_1) = \frac{1}{1 + \frac{6}{9} + \frac{1}{9}} = 0{,}5625, \tag{5.17}$$

$$e_{low}(e_2) = \frac{1}{\frac{9}{6} + 1 + \frac{1}{6}} = 0{,}375, \tag{5.18}$$

$$e_{low}(e_3) = \frac{1}{9 + 6 + 1} = 0{,}0625. \tag{5.19}$$

Similarly, the matrices of pair comparisons of various alternative energy sources are determined in terms of their proximity to the term "medium" and "high".

Table 5.3 – Paired comparisons of non-traditional energy sources in accordance with their proximity to the term "medium"

		e_1	e_2	e_3
$A_{medium}(e)=$	e_1	1	9 / 1	6 / 1
	e_2	1 / 9	1	6 / 9
	e_3	1 / 6	9 / 6	1

Table 5.4 – Paired comparison of alternative energy sources according to their proximity to the term "high"

		e_1	e_2	e_3
A_{high} (e)=	e_1	1	1 / 6	9 / 6
	e_2	6 / 1	1	9 / 1
	e_3	6 / 9	1 / 9	1

According to the data of the Table 5.3 the degrees of membership of the elements e_1, e_2, e_3 are obtained, to the term "average":

$$e_{\text{medium}}(e_1) = \frac{1}{1+9+6} = 0{,}0625, \tag{5.20}$$

$$e_{\text{medium}}(e_2) = \frac{1}{\frac{1}{9}+1+\frac{6}{9}} = 0{,}5625, \tag{5.21}$$

$$e_{\text{medium}}(e_3) = \frac{1}{\frac{1}{6}+\frac{9}{6}+1} = 0{,}375. \tag{5.22}$$

According to the data of the Table 5.4 the degrees of membership of the elements e_1, e_2, e_3 are obtained to the term "high":

$$e_{\text{high}}(e_1) = \frac{1}{1+\frac{1}{6}+\frac{9}{6}} = 0{,}375, \tag{5.23}$$

$$e_{\text{high}}(e_2) = \frac{1}{6+1+9} = 0{,}0625, \tag{5.24}$$

$$e_{\text{high}}(e_3) = \frac{1}{\frac{6}{9}+\frac{1}{9}+1} = 0{,}5625. \tag{5.25}$$

The obtained values of membership functions are normalized per unit by dividing by the highest degree of membership. As a result, different levels of use of alternative energy sources are presented in the form of such fuzzy sets [62]:

– alternative energy source "low"

$$_{e} = \left\{ \frac{0{,}5625}{1}; \frac{0{,}375}{2}; \frac{0{,}0625}{3} \right\};$$

– alternative energy source "average"

$$_{e} = \left\{ \frac{0{,}0625}{1}; \frac{0{,}5625}{2}; \frac{0{,}375}{3} \right\};$$

– alternative energy source "high"

$$_{e} = \left\{ \frac{0{,}375}{1}; \frac{0{,}0625}{2}; \frac{0{,}5625}{3} \right\}.$$

Fuzzy sets characterizing membership functions for the linguistic variable "alternative energy sources" are shown in Fig. 5.7.

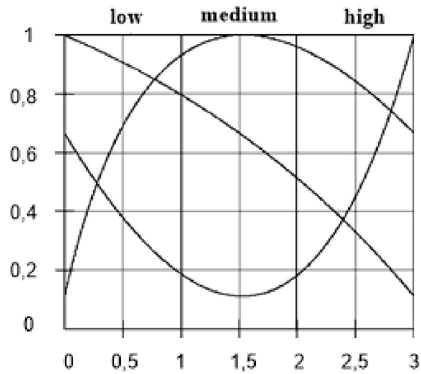

Figure 5.7 – Functional features for the linguistic variable "alternative energy sources"

As a result of constructing charts of the functions of belonging to Fig., graphical models of the dependence of the efficiency of the power supply system of an unmanned aircraft on the use of various non-traditional energy sources were obtained. The received knowledge base on the connections of fuzzy terms of input and output linguistic variables allows optimizing the choice of effective configuration of the power system of an unmanned aerial vehicle.

The structure of the airborne complex of electric power supply of the UAV with the use of additional sources of electric energy and additional power plants based on short-circuited asynchronous motors is proposed.

It is determined that the main among the indicators of aircraft autonomous power systems are their energy efficiency, reliability and mass-size. The structure of the hierarchical neuro-fuzzy network of energy efficiency of the power supply system of an unmanned aerial vehicle with the use of alternative sources of electric power is proposed.

Fuzzy matrix of knowledge about the relation at the systemic level of influence of non-traditional energy sources is given.

A system of fuzzy logical equations is made up to linguistic statements that characterize the dependence of variables on the corresponding terms.

Defazification at the level of alternative sources of electricity has been carried out; the degree of membership of the elements has been defined to the terms "low, medium, high".

The use of alternative sources of electricity is presented in the form of fuzzy sets, which are described by the membership functions for the linguistic variable "alternative sources of electricity".

CHAPTER 6
ASPECTS OF MODERN AVIATION MATERIALS SCIENCE

6.1 The main properties of structural materials

Physical and chemical properties of materials.

Construction materials are characterized by various properties that determine the quality of materials and their scope. On a number of grounds, the basic properties of materials are divided into physical, mechanical, technological and chemical.

The physical properties of the material characterize its structure or relation to the physical processes of the environment. All construction materials with density, thermal conductivity and heat capacity. For metals, important physical characteristics are melting point and electrical conductivity. Building materials are also characterized by density, hygroscopicity, frost resistance, fire resistance.

The density of the material is determined by the ratio of mass to volume of the material in an absolutely dense material ρ [60].

Most building materials have a hollow structure, so they are characterized by density or average density $\rho_{m.}$. Dense materials (steel, glass, bitumen, etc.) have almost the same density and density.

The density of the material depends on its hollowness and humidity. Artificial materials, such as concrete, can be obtained with varying degrees of voids.

Bulk materials (sand, cement, gravel, etc.) are characterized by bulk density.

The main chemical properties of structural materials are chemical and corrosion resistance.

Chemical resistance – the ability of materials to counteract the destructive effects of alkalis, acids, salts and gases dissolved in water.

Corrosion resistance – the ability of materials to counteract the corrosive effects of the environment. Many construction materials do not have sufficient corrosion resistance. So most cements are destroyed by acids, bitumen is not resistant to alkali solutions, wood and carbon steel have low corrosion resistance. Precious metals, titanium, aluminum and most of their alloys, special steels, dense ceramics and most plastics have the best corrosion resistance.

Mechanical properties of materials.

Mechanical properties include strength, elasticity, ductility, hardness, toughness, endurance, wear resistance, and others. Its behavior during deformation and destruction under the action of external forces depends on the mechanical properties of the material. To determine them, metal samples of the specified size and shape are tested on special machines and devices under certain conditions. Test conditions are divided into static (sample loads increase slowly and smoothly), dynamic (load increases with high speed and has a shock character) and cyclic (loads change repeatedly in magnitude and direction).

Static loads during tests can be tensile and compressive. Metals are most often tested for tensile strength, which determines the limits of elasticity, fluidity and strength and its ductility.

Strength and ductility of metal.

The strength and ductility characteristics are obtained by stretching the sample in the form of a round rod or strip. The dependence of the elongation of the sample on the load is recorded on special machines. Based on these data, a diagram of the dependence of the relative elongation of the sample δ on the stress σ is constructed.

The type of diagram significantly depends on the plasticity of the material, which characterizes the ability, without collapsing, to change shape under the action of the load and store it after the load ceases to act.

The segment OA of the diagram corresponds to the elastic deformation of the metal when Hooke's law $\sigma = E \cdot \delta$ holds, where E is the modulus of elasticity (Young's modulus).

The stress corresponding to the ultimate elastic deformation at point A is called the limit of proportionality σa (or the limit of elasticity). In the SI system it is expressed in MPa. At higher stresses, there is a uniform plastic deformation (elongation and narrowing of the transverse cross section) of the sample. Since it is almost impossible to determine the beginning of the transition of the metal to the inelastic state, the elastic limit is set conditionally, given the residual deformation, often 0.001; 0.005; 0.02 and 0.05%. The elastic limit is denoted by σ0.01; σ0.05, etc. This characteristic is important for spring and other materials.

Many plastic materials at stresses slightly higher than σa have a section on the tensile diagram in which the sample is deformed without increasing the load. The stress corresponding to this state of the material is called the yield strength and is denoted by σ_T. The stresses acting in the part must be less than the yield strength.

Further stretching of the sample is accompanied by a uniform increase in stress to σ_v – the tensile strength (ability to resist destruction under the action of external forces). This stress is the largest and corresponds to the beginning of a large plastic deformation of a non-large area of the sample, called the neck. It is here that the cross section of the sample is significantly reduced and destruction occurs.

Semi-brittle materials are destroyed at stresses equal to $\sigma_в$ in brittle ones there is no yield area.

The tensile diagram determines such plasticity characteristics as relative elongation δ and relative narrowing Ψ. The relative elongation characterizes the increase in the length of the sample relative to the initial, and the relative narrowing – relative to the decrease in the cross-sectional area [70]:

$$\delta = \frac{l_1 - l_0}{l_0}$$

where l_1 and l_0 are the length of the sample before and after deformation;

$$\psi = \frac{S_1 - S_0}{S_0} \cdot 100\%$$

where S_1 and S_0 – respectively, the cross-sectional area of the sample before and after the tests. The plasticity indicators determine the suitability of the material for plastic deformation during pressure treatment, as well as its ability to redistribute stress during overload. These data are important for both designers and technologists. For example, plastic materials are more reliable because they are less likely to break dangerously brittle.

Strength of non-metallic materials.

Materials of mineral origin (stone, brick, concrete, etc.) work well on compression, so they are used in appropriate structures. The strength of such materials is determined by compressing samples of certain sizes on presses. The compressive strength is defined as the ratio of the force applied to the sample to the cross-sectional area of the sample. The brand (4, 7, 10, 15, 25, 35, 50, 75, 100, 125, 150, 200, 300, 400, 500, 600, 800, 1000) is set for the strength of stone materials. Thus, materials with a compressive strength of 20 - 29.9 MPa belong to the brand 200.

Wood materials are also tested for tensile and compressive, determining the appropriate strength limit in MPa.

Strength also depends on the structure of the material, its density, humidity, the direction of action of the applied force.

Construction materials are also tested for flexural strength of samples of certain sizes. Samples in the form of beams placed on two supports are tested for bending. A certain force is applied to the middle of the beams, which gradually increases until the samples are destroyed. According to the applied force and the sizes of a beam define a limit of durability on a bend. This tensile strength depends largely on the profile of the product.

Hardness.

Static compression of metal with a special indenter is used to determine hardness – the ability of a metal to resist elastic and plastic deformations during the penetration of another harder body. The most commonly tested hardness of metals by the methods of Brinell, Rockwell and Vickers.

Determination of hardness by the Brinell method is reduced to pressing into the test material a hardened steel ball of a certain diameter, which is subjected to a force F for a time sufficient to complete the plastic deformation in the metal. The diameter of the impression is measured and the hardness (HB) is determined from the tables.

According to the Rockwell method, the hardness is determined by the depth of penetration of a diamond cone or ball with a diameter of 1.6 mm, expressed in conventional units (HPC, HPA or HPB). The hardness of hard, very hard and soft materials is determined by the Rockwell method. Accordingly used a diamond cone with an angle of 120 ° and a total load of 1.47 kN (scale C), a diamond cone and a total load of 0.59 kN (scale A) and a steel ball with a load of 0.98 kN (scale B). First, a preliminary force F0 is applied to the indexer, under the action of which it sinks into the metal by the value of h_0. Then gradually add the main force F1. The unit of hardness is the value corresponding to the axial displacement of the indenter by 0.002 mm.

The Vickers method is used to determine the hardness of parts of small thickness and thin very hard surface layers of metal parts. The load during the tests is 0.05... 1.20 kN. The micro-hardness method is used to determine the hardness of individual grains or very thin layers of metal.

The hardness of wood and concrete is also determined by pressing into a steel ball. The amount of hardness is determined by the diameter or depth of the impression.

The hardness of natural stone materials is determined by a hardness scale (Mohs method), in which ten specially selected materials are placed in such a sequence that the next mineral leaves a mark (scratch) on the previous one.

Impact strength, durability and wear resistance.

The main type of testing of metals under dynamic loads is the test for impact bending of incised samples of standardized size. Impact strength is the ratio of the work expended on the destruction of the sample to the initial cross-sectional area at the site of failure. The incised sample is mounted on a pendulum swing and struck with a pendulum.

Most parts of machines and structures operating under cyclic loads are destroyed after a certain number of cycles at stresses below σT. This phenomenon is called fatigue. To characterize the strength of the metal in such conditions use the endurance limit σ-1 – the highest stress at which the part does not break after a certain number of load cycles, called the base. For steel, it is 107 cycles, and for non-ferrous metals – 108. Studies are conducted on test machines, often with a rotating sample. Construction materials are tested for wear resistance on special rotating drums.

Because it is difficult to fully reproduce the operating conditions of a part in a structure or machine during standard tests, ready-made parts are often additionally tested on stands or during operation. Although it is expensive, it allows you to make more informed decisions when choosing a material and how to strengthen it.

6.2 Structural metals and alloys

The main provisions of the theory of alloys. Iron-carbon alloys.

Basic concepts of alloys.

Pure metals in most cases do not provide the required set of mechanical and technological properties and are therefore rarely used for the manufacture of parts. In most cases, the technique uses alloys.

An alloy is a substance that consists of two or more components.

Most alloys are obtained in the liquid state, but they can also be obtained by sintering, electrolysis, condensation from the vapor state, and so on. Non-metals (metalloids) may be included as components in the composition of metal alloys, but metals predominate.

Not every compound of components gives an alloy. Iron and lead, for example, in the liquid state are divided into two layers, and the alloy of these components becomes impossible.

A necessary condition for the manufacture of alloys with mutual diffusion of atoms of components. This condition is most easily satisfied when the components are in a liquid state and form homogeneous solutions at the atomic level. During crystallization, depending on the physicochemical properties of the components, their atoms interact. As a result of such interaction structures are formed in the form of:

– solid solution of substitution or penetration;

– chemical compound;

– mechanical mixture of dissimilar crystals, etc.

In a solid substitution solution, the atoms of the dissolved component replace part of the atoms of the solvent component in its crystal lattice. The number of substituted atoms can vary over a wide distance. Depending on this, there are solid solutions with unlimited and limited solubility. For the formation of such solutions it is necessary to choose components in which [71]:

– the same type of elementary crystal lattice;
– the difference in the size of atomic radii does not exceed 8... 15%;
– close structure of valence atomic levels of components.

In solid solution penetration, the atoms of the dissolved component can be located in the interatomic cavities of the spatial crystal lattice of the solvent component.

Due to the small size of the cavities of the crystal lattice of the solvent metal, it can be argued that they can contain only non-metal atoms with small dimensions (carbon, hydrogen, boron).

Solid penetration solutions are only limited, the concentration of the dissolved component in them does not exceed 2%.

A chemical compound is most often formed from elements that differ significantly in structure and properties. The ratio of the number of atoms of the elements that make up a compound is strictly defined and is expressed by a certain formula. The elementary crystal lattice of a chemical compound is different from the crystal lattice of the components that formed it. The chemical elements in it occupy strictly defined positions. The properties of a chemical compound differ significantly from the properties of the components. Preferably chemical compounds are characterized by low ductility and high hardness, which significantly exceeds the hardness of the components. Unlike solid solutions, chemical compounds have a constant melting point.

The mechanical mixture consists of heterogeneous crystals. This structure is a very fine mixture of crystallites (grains) components. Mechanical mixtures are formed in cases where the elements have limited solubility and do not form a chemical compound.

The concept of systems, phases, components.

When studying the processes occurring in alloys during their transformation, and when describing their structure in materials science use the following concepts: system, phase, component.

The system is called a set of phases that are in equilibrium under certain external conditions (temperature, pressure). Systems (alloys) are simple and complex.

The phase is called the homogeneous in chemical composition, crystalline structure and properties of the part of the system, separated from other parts of the system by the interface. The phases can be liquid and solid solutions, chemical compounds. A single-phase system is, for example, a homogeneous liquid, and a two-phase system is a mechanical mixture of two types of crystals.

The components are the substances that make up the system. The components can be elements (metals and non-metals), as well as stable chemical compounds.

State diagram of alloys.

The state diagram of alloys is a graphical representation of the state of the alloy depending on the concentration and temperature. Diagrams of the state of alloys should be learned to understand that [73]:

– to predict phase transformations in alloys of different concentration at temperature change during technological processes of manufacturing or in working conditions;

– evaluate the nature and properties of equilibrium phases and structures formed in alloys at different temperatures;

– based on knowledge of the factors influencing the processes of crystallization and recrystallization, to predict possible changes in the structure and properties of the alloy with inevitable deviations from the conditions of equilibrium crystallization in real processes;

– to use the influence of the phase and structural state of alloys on the mechanical and technological properties when designing the final structure of the material of the part.

State diagrams of alloys are constructed from experimentally determined critical points in alloys of different concentrations. The method of experiments is based on the fact that any phase transformation is accompanied by a change in physical and mechanical properties (electrical resistance, specific volume, etc.) or thermal effect. The crystallization of the alloy is accompanied by a significant release of heat, so the moments of beginning or end of the process or its course at a constant temperature on the graphs of the cooling rate – cooling curves – will correspond to the inflections of the curve or horizontal sections.

State diagrams are constructed in temperature-concentration coordinates. The extreme coordinates will correspond to the pure components. On the vertical concentration of each investigated alloy, points corresponding to the temperatures of the beginning and end of crystallization and allotropic transformations are plotted. Accordingly, the end points of crystallization give the solidus line, below which all alloys are in the solid state.

Non-ferrous metal alloys.

Copper alloys. Composition, structure, properties, marking and use of brass and bronze [74].

Brass is called an alloy of copper with zinc. They are simple (if they contain only copper and zinc) and multicomponent (when they contain other chemical elements in addition to copper and zinc). Brass with a zinc content of up to 45% has a technical application.

In the grades of single-phase brass write the letter "L" and a number indicating the average percentage of copper. In the brands of alloyed brass, in addition to the number indicating the copper content, write the letters and numbers that indicate the presence of a particular element and its percentage content. Aluminum in brass is denoted by the letter "A", nickel – H, tin – O, lead – C, phosphorus – F, iron – F, silicon – K, manganese – Mts, beryllium – B, zinc – C. In deformable brass recorded first all letters, and then numbers through a hyphen – the content of alloying elements, for example, LAN59-3-2 contains 59% Cu, 3% A1 and 2% Ni. In the brands of cast brass, the copper content is not written, and after the letter "L" write the letters and numbers – the percentage of available elements, for example, LC40MtsZA contains 40% Zn, 3% Mn, 1% A1 and 56% Cu.

Bronze is an alloy of copper with all the elements except zinc, which may be present in small quantities as an alloying element. Bronze is named after the main component (besides copper) (tin, aluminum, siliceous, lead, beryllium, etc.).

The most common and long known is tin bronze. For centuries, machine or cannon bronze with a tin content of 9... 12%, artistic – 3... 8% Sn, coin – 4... 5% Sn, and also bronze for bells with 20... 25% Sn. Bronzes with a tin content of up to 10% have practical application. In order to reduce the cost and to improve the technological properties of tin bronzes are doped with zinc, lead, nickel and phosphorus [79].

Deformable single-phase bronzes are marked with the letters "Br" (bronze), letters "O, C, C, F, H" and numbers through a hyphen, indicating the content of tin, zinc, lead, phosphorus and nickel, respectively, as a percentage, for example, BrOCS 4-4-2.5 contains 4% Sn, 4% Zn s 2.5% Pb. These bronzes have high electrical conductivity, corrosion resistance and antifriction properties, as well as elastic properties and fatigue resistance. Therefore, they are used to make round and flat springs in precision mechanics (watches), electrical engineering, chemical engineering and other industries.

In cast bronze grades, the content of each alloying element is written immediately after the letter, for example, BrOZTs7S5N1 contains 2.5... 4.0% Sn, 6.0... 9.5% Zn, C... 6% Pb and 0.5... 2.0% Ni. Foundry bronzes have high antifriction properties (BrOZTSI2S5, BrO4-Ts4S17, BrO10Ts2). High corrosion resistance of bronzes in atmospheric conditions, in sea and fresh water allows to use them for steam-water fittings working under pressure. Modern casting technologies allow the valve to withstand pressures up to 30 MPa.

Aluminum is a substitute for expensive tin bronzes. They have slightly higher mechanical properties, high fluidity, slightly higher shrinkage, good tightness and low tendency to dendritic segregation. Single-phase bronzes (BrA5, BrA7) have high ductility and at the same time high strength (σ_B = 400... 450 MPa, δ = 60%). They are used to make electrical contacts and chemically resistant parts. Two-phase aluminum bronzes are more often foundry, have high strength (σ_B = 600 MPa) and hardness (> 100 HB). They can be thermally strengthened.

Pure aluminum bronzes also have many disadvantages: high shrinkage, tendency to gas saturation and oxidation during melting, large crystalline structure, poorly soldered. To eliminate these shortcomings, aluminum bronzes are alloyed with iron, nickel and manganese.

Iron modifies aluminum bronzes, increases their strength, hardness and antifriction properties, reduces the tendency to brittleness. Heat treatment of iron-doped bronzes, for example BrAZh9-4 (normalization or hardening and tempering), allows to increase hardness to 175... 180 HB. They are used to make corrosion-resistant screws, shafts, etc. Nickel improves the technological and mechanical properties of aluminum-iron bronzes at normal and elevated temperatures. Aluminum-iron-nickel bronzes are used to make parts that work in difficult conditions of abrasion at high temperatures (400... 500 ° C): valve seats, exhaust valve bushings, pump and turbine parts, gears and other parts. High mechanical properties are characteristic of aluminum-ferrous bronzes doped with cheaper manganese (BrAZhMts10-3-1,5). Heat-resistant parts are made of them.

Siliceous bronzes are characterized by high mechanical, elastic and antifriction properties. They are well welded and soldered, arbitrarily processed by cutting and have low compared to other bronzes and brass casting properties. To increase the casting properties, they are doped with zinc, manganese and nickel. Lead improves anti-friction properties and machinability by cutting. Siliceous bronzes are used instead of more expensive tin for the manufacture of antifriction parts [68].

Beryllium bronzes have very high limits of elasticity and strength, hardness and corrosion resistance together with increased resistance to fatigue, creep and operation. These bronzes are heat-resistant up to 310... 340 ° C, have high thermal and electrical conductivity, are well welded by spot and seam welding, practically are not welded by melting. Beryllium bronzes (BrB2) are used to make very responsible springs (carburetors, fuel pumps), elastic contacts, membranes, parts that work on abrasion (cams, gears, worm wheels), plain bearings for high temperatures. temperatures, velocities and pressures. Beryllium bronze is an intrinsically safe material (does not create sparks when hitting a stone or metal). Therefore, it is used to make electrical contacts and percussion tools for work in explosive conditions (miners' tools). The main disadvantage of beryllium bronzes is their high cost. Therefore, 0.1... 0.3% Be is replaced by Mn, Ni, Ti, Co (BrBNT1.7; BrBNT1.9) without reducing the mechanical properties.

Lead bronzes combine high antifriction properties with high thermal conductivity, toughness and fatigue strength. Therefore, they are used to make high-load plain bearings for high speeds (aircraft and diesel engines, powerful turbines). Such bronzes contain up to 25... 30% Pb. To increase the strength and hardness, these bronzes are alloyed with copper, soluble tin, nickel, and manganese (Br CH60-2.5).

Copper alloys with nickel are called cupronickels (20... 30% Ni, the rest of the copper), kunials (5... 15% Ni, 1.2... 3.0% Al), nickel silver (13.5... 16.5% Ni, 18... 22% Zn or 1.6... 2.0% Pb). All of them are corrosion-resistant in the atmosphere, sea and fresh water, many organic liquids, salt solutions, etc., as well as non-magnetic [66].

Aluminum alloys. Composition, structure, properties, labeling and application of silumins, duralumin, high-strength and heat-resistant alloys.

Aluminum alloys are characterized by high specific strength, ability to withstand inertial and dynamic loads and high technological properties. Most aluminum alloys have good corrosion resistance (except for copper alloys), high thermal and electrical conductivity, are well pressurized, spot welded, and some are melted, well machined by cutting, aluminum alloys are more ductile than magnesium alloys and most plastics.

The main components of aluminum alloys are copper, magnesium, silicon, manganese and zinc, sometimes using lithium, nickel and titanium.

Aluminum alloys are classified by the technology of manufacturing parts (deformable, cast, powder), by suitability for heat treatment (hardened and unstrengthened) and by properties.

Deformable aluminum alloys are separated according to their suitability for heat treatment. Non-reinforceables include alloys of the Al-Mn system, marked with the letters AMc and a number – the alloy number, and alloys of the A1-Mg system, in the grades of which the letters AMg and the alloy number are written. These alloys are suitable for conditions requiring high corrosion resistance, such as gasoline and lubricant pipelines, welded tanks, and the like. Rivets, partitions, hulls and masts of ships, parts of elevators, car frames, car bodies, etc. are also made of AMg and AMts alloys, which have a tensile strength of 110... 430 MPa.

Aluminum alloys that are strengthened by heat treatment are divided into alloys with normal strength – duralumin, in the brands of which write the capital letter D and the number of the alloy, and high-strength, in the brands of which write the capital letter "B" and the number. Among the deformable alloys are alloys for pressure treatment – forging. The letters "AK" and the numerical number of the alloy are written in their stamps.

Duralumin is characterized by a good ratio of strength and ductility and belongs to the alloys of the A1-Cu-Mg system. Duralumin has low corrosion resistance, so their surface is covered with a thin layer of pure aluminum – weeping. The thickness of the aluminum layer is 3... 5% of the sheet thickness. Soldering and welding of duralumin do not create a uniform seam with the base metal. Therefore, riveted joints predominate for the permanent connection of duralumin parts. Rivets are also made of duralumin, and the plasticity of hardened rivets from alloy D1 lasts only 2 hours, and from alloy D16 – 20 minutes. Therefore, the D18 alloy is used for rivets, in which the plasticity is preserved even after aging due to the lower content of copper and magnesium.

Duralumin is widely used in aviation, construction and mechanical engineering (propeller blades (D1), frames, control rods (D16), building parts, truck bodies, casing, etc.).

Ductile aluminum alloys (AK4-1, AK-4), in addition to high strength, have high ductility in the heated state. In chemical composition they are close to duralumin and have a higher content of silicon. They are additionally alloyed with iron, nickel and titanium. These alloys are used for the manufacture of pistons, cylinder heads, aircraft planes.

Foundry aluminum alloys at a density of 2.65 t / m^3, which is less than the density of pure aluminum, have a tensile strength of 130 to 360 MPa and a hardness of 50 to 100 HB. These alloys are divided into 5 groups.

The most common are silumins, which contain 6 … 13% silicon. They weld well, have high fluidity, low shrinkage, are not prone to hot cracks, airtight. Marked with the letters AK (silicon bridge in%). AK12, AK9, AK7, etc. are used for light and medium-loaded cast parts of complex shape.

Copper silumins (AK5M, AK8M3, AK12M2MgN, etc.) are characterized by high strength at normal and elevated temperatures. They are well cut and welded, but the casting properties are worse. Are applied to production of cases of compressors, heads and blocks of cylinders of engines [64].

Castings also include alloys of the A1-Cu (AM5) system have the highest strength, are well processed by cutting and welded. The casting properties of these alloys are low.

Antifriction alloys, powder and composite materials.

Metal glass

1. Antifriction alloys.

Antifriction properties are provided by the structure: soft base – solid solution and solid inclusion – eutectoid ($\alpha + \delta$). Tin and lead bronzes have good antifriction properties. Lead bronze has a structure consisting of α-phase grains and lead-based eutectic (99.96%), which is located at the grain boundaries or in the interdendritic spaces. However, tin bronzes are expensive and lead bronzes have low technological properties and strength. Therefore, BrS30 bronze is better used as a deposited working layer in bi- and trimetals. If lead bronzes are alloyed with nickel and tin (Br.OS8-I2, Br.OSN 10-2-3, etc.), they can be used for the manufacture of bushings and bearing inserts without a steel base. Because tin and lead are scarce metals, aluminum-based alloys are often used [73].

Aluminum alloys have good antifriction properties, high thermal conductivity, good corrosion resistance in oily media and good mechanical and technological properties. They are used in the form of a thin layer, which is applied to a steel base. Depending on the chemical composition, there are two types of alloys:

1. Aluminum alloys with antimony, copper and other elements that form solid phases in a soft aluminum base. The most common alloy AFM, which includes antimony (up to 6.5%) and magnesium (0.3-0.7%) This alloy works well at high speeds and high loads under liquid friction and is used for the manufacture of crankshaft bearings engines of tractors and cars.

2. Aluminum alloys with tin and copper, for example, A020-1 (20% tin and up to 1.2% copper) and A09-2 (9% tin and 2% copper). They work well in dry and semi-dry friction and are close to babbits in antifriction properties. They are used for the manufacture of bearings in the automotive, tractor and general engineering industries.

Cast irons are sometimes used as antifriction alloys. They have a pearlitic base and high graphite content. Graphite acts as a lubricant.

Anti-friction cast irons are used to make worm gears, slider guides, and more.

Recently, powder materials are widely used as antifriction materials. They are made of bronze or iron powders with the addition of 1-3% graphite, impregnated with oil, which fills the pores, the volume of which in the product is 15-30%. Lubricant and graphite lubricate the friction surfaces. Wear of bearings and a neck of a shaft is 7-8 times less, than at babbits. The service life of porous bearings is 1,5-10 times longer than standard ones.

Depending on the conditions of use, such bearings have different requirements. Thus, turbo and aircraft construction requires resistance to high temperatures, work without lubrication. Such powder materials are made of powders of metal oxides (up to 90%) or metal mica, graphite, powders of iron + graphite + sulfide additives, which reduce the coefficient of friction.

2. Powder and composite materials.

Powder materials or sintered materials are made from metal powders, their alloys and refractory compounds (carbides, nitrides, borides, etc.) by powder metallurgy. They are characterized by such unique properties that they can be given to materials in many cases only by powder metallurgy, rationally combining charge (source) components. In addition, the creation of powder materials requires minimal material losses [75].

By purpose, there are powder materials: structural, antifriction, friction, electrical contact, tool, magnetic, porous, corrosion-resistant. There are powder alloys of copper, refractory metals and more.

Structural powder materials are made mainly of iron powder. They are used in the manufacture of machine parts. Bronze, stainless steel powders, etc. are used for antifriction materials. Bearings are made of them. The basis of some friction materials are iron powders with special additives. These materials are used in the brake systems of heavy-duty vehicles.

Bronze-based friction materials are used in the friction units of many transport, road and other machines. Contacts of high-voltage and high-power switches and other devices are made of electrocontact powder materials based on tungsten and silver powder, tungsten and copper, and cutting tools are made of tool powder materials based on, for example, steel powder. Magnetic powder materials are used for magnetic circuits of various devices, relays, electromagnetic couplings; porous – for filters that clean air, liquids, fuel, etc.; corrosion-resistant – for devices of the chemical industry.

Alloys obtained from metal powders by pressing and subsequent sintering without melting, are called powder, and the method of production - powder metallurgy.

Powder metallurgy technology provides products from a single metal, such as iron (such products are called one-component), as well as from a mixture of metal powders or metals with non-metals (multi-component products). This technology can be used to obtain alloys from metals that do not form solutions, do not mix in the liquid state (iron – lead, tungsten – copper, etc.), as well as from metals with nonmetals (copper – graphite, tungsten carbide – cobalt, etc.).

Savings are due to the replacement of precious non-ferrous metals and alloy steels, reduces the complexity of manufacturing products, as well as electricity costs, transportation and other costs.

The powder material consists of particles of metal or alloy up to 1 mm in size that are in contact with each other and not connected to each other. Metal particles almost always contain impurities distributed both on the surface and in the form of internal inclusions, and often have pores.

The powder can be obtained by chemical-metallurgical and physical-mechanical methods.

Sintering is the heating and holding of compressed powders at a temperature below the melting point of the main component in order to ensure the specified mechanical and physicochemical properties. For one-component systems, the technological sintering temperature is 0.6-0.9 of the melting point of the main component. Multicomponent systems are sintered at the melting point of the most fusible component.

In the process of sintering, a strong powder body is formed with properties that are close to the properties of a compact non-porous material.

By the method of powder metallurgy it is possible to obtain such alloys which are difficult or impossible to obtain by other known methods. For example, various alloys of metals: tungsten-copper, tungsten-silver, etc., as well as metals and non-metals: copper-graphite, silver-cadmium oxide, etc., which are widely used in electrical and radio engineering.

3. Metal glass.

The first work on obtaining amorphous films using vacuum spraying appeared in the 50s. Later, amorphous alloys were obtained by electrodeposition of alloys. In 1960, scientists Sally and Miroshnichenko developed a method for producing amorphous alloys by double-sided cooling of melts. The achieved cooling rates of the melt were ~ 106 K / s. Cohen and Terenbell showed that the amorphous composition of Au-Si is close to the composition of an alloy with a very low eutectic point on the equilibrium diagram. A simple condition for the formation of amorphous metal alloys is established – deep eutectic on equilibrium state diagrams, which in turn facilitated the search for systems and compositions that can be amorphized during quenching from the melt.

Amorphous metals are metastable systems that are thermodynamically unstable to the crystallization process. Their existence is due only to the slowness of kinetic processes at low temperatures. Stabilization of amorphous metals is facilitated by the presence of so-called amorphous impurities. Thus, amorphous films of pure metals are much less stable than films of alloys.

Very high cooling rates (~ 1010 K / s) are required to obtain metallic glass from pure metals [74].

Many metallic glass has unique mechanical, magnetic and chemical properties. The yield strength and strength for a number of metallic glass are very high and close to the so-called theoretical limits. At the same time, metallic glass has a high ductility, which sharply distinguishes them from dielectric and semiconductor glass. A large amount of metallic glass with high mechanical strength is characterized by high initial magnetic susceptibility, low values of coercive forces and almost complete absence of magnetic hysteresis. The corrosion resistance of some metal glass is several orders of magnitude higher than that of many of the best stainless steels.

Other unique features of metallic glass include poor sound absorption and catalytic properties. The main features of metallic glass are obviously due to their high microscopic homogeneity, ie the absence of structural defects such as intergranular boundaries, dislocations, etc.

When a metal or alloy melts, the crystal lattice collapses and the atoms in the liquid oscillate around positions that are constantly and rapidly redistributed to each other. When melting, the liquid and solid phases are in equilibrium, enthalpy and entropy undergo an abrupt change. At temperatures above the crystallization point, the liquid phase is in a state of internal equilibrium and is unable to resist shear stress. Metal melts are characterized by viscous fluidity, while melts of silicates, borates and other similar substances have a very low fluidity, ie have a high viscosity.

During cooling, before the crystallization process begins, the liquid phase must be supercooled below the equilibrium crystallization temperature, in order to overcome the energy barrier required to create a crystal nucleus. The degree of supercooling of the melt depends on a number of factors, including the primary viscosity of the melt, the rate of its growth with decreasing temperature; temperature dependence of the difference of free energies of liquid and crystalline phases; density and efficiency of centers of heterogeneous nucleation; cooling rate.

When the centers of heterogeneous nucleation (impurities) are removed from the melt, the growth rate of the crystals remains very high, and in the case of a low rate of heat dissipation into the environment, the volume is rapidly filled with the crystalline phase. If the melt is cooled quickly (providing efficient heat dissipation), the influence of sources of heterogeneous crystal formation is difficult, and in the case of an even greater increase in the cooling rate, the supercooling increases even more and the rate to crystallization decreases [75].

Thus, the temperature interval in which the crystallization process takes place is significantly reduced, which causes a change in the structure formed during cooling. First, the microcrystalline structure is ground, and then, depending on the composition of the alloy, the solubility in the solid solution expands and metastable crystalline phases are formed. And if the cooling rate is very high, crystallization is inhibited and there is a slowdown not only in the growth of crystals, but also their origin.

The viscosity of the melt cools continuously. Despite the fact that the driving forces of crystallization are constantly increasing, they are nevertheless compensated by the rapidly decreasing mobility of atoms, which dominates at very large values of supercooling. As a result, the atomic configuration becomes non-equilibrium and at the so-called glass temperature T_g is homogeneously frozen. In practice, several amorphous structures can correspond to one alloy, because the temperature and the structure at which the deviation from the equilibrium state depends on the cooling rate.

6.3 Corrosion of metals and methods of protection against it

The concept of corrosion

Corrosion of metals and alloys is their destruction under the influence of the external environment.

All metals and alloys used in engineering corrode to one degree or another; only gold and platinum do not corrode under normal conditions.

Examples of corrosion include atmospheric rusting of iron, corrosion of underwater parts of ships, and damage to chemical equipment under the influence of solutions of salts, acids, or alkalis. Corrosion leads to partial or complete failure of individual parts or the entire product.

About 2% of all metals and alloys used in the world are lost annually from corrosion.

Depending on the environment in which the process takes place, there are electrochemical and chemical corrosion.

Electrochemical corrosion

Electrochemical corrosion is such corrosion that is accompanied by the appearance of an electric current. Most often, electrochemical corrosion of metals occurs in liquids – electrolytes. Electrolytes can be acids, alkalis, their solutions, solutions of salts in water, water containing dissolved air.

Metal atoms consist of positively charged ions that oscillate near their middle position in the crystal lattice and move chaotically inside the spatial lattice of negatively charged electrons.

When the metal is immersed in the electrolyte, the ions that are on the surface, go into solution in an amount that depends on the nature of the metal and the electrolyte. This process of dissolving metals in an electrolyte is similar to the usual dissolution of, for example, salt in water, which ceases when the solution becomes saturated. However, when the metal dissolves, only positively charged ions pass into the electrolyte, as a result of which the electrolyte adjacent to the metal plate is positively charged, and the plate itself is negatively charged, due to the remaining electrons. All metals have different ability to pass into solution, ie different degrees of dissolution, so if the plates of different metals are lowered into one electrolyte, they will have different potentials, and the more metal ions go into solution, the greater the negative potential of this metal [76].

When the various metal plates in the electrolyte are connected, galvanic pairs are formed, where the anode is a metal with a lower potential and the cathode is a metal with a higher potential. In galvanic steam, the transition of anode ions into solution will continue until complete dissolution of the anode plate. Thus, if the zinc plate and the iron plate are lowered into the electrolyte and connected electrically, the zinc will dissolve until the plate is completely destroyed.

The structure of technical metals and alloys in most cases is heterogeneous and consists of two phases (eg, ferrite and cementite). When such an alloy is immersed in an electrolyte, its individual inhomogeneous crystals will have different potentials, and due to the fact that these crystals are electrically closed to each other through a mass of metal, the alloy will be a large number of individual galvanic micropairs. This shows that pure metals and single-phase alloys must have greater corrosion resistance than alloys consisting of a mixture of phases. Experiments have shown that steel hardened to martensite rusts much less than the same steel after annealing or high tempering (state of perlite, sorbitol or troostite).

The electrolyte layer during corrosion can be quite insignificant: a small enough condensation of moisture from the air on the surface of the metal, as the process of its rusting begins, so electrochemical corrosion is observed indoors.

Chemical corrosion

Chemical corrosion is corrosion that is not accompanied by the appearance of an electric current. Usually in this case the metal is exposed to dry gas or liquid – non-electrolyte (gasoline, oil, resin, etc.). At the same time, chemical compounds are formed on the surface of the metal, most often oxide films. The strength of films of oxides of different metals is different. For example, films of iron oxides are fragile, and aluminum film is quite strong, close to the surface of the metal and thus protects it from further destruction.

The presence of a strong oxide film protects the metal from electrochemical corrosion, because it acts as an insulator. This explains the fact that some metals (eg, aluminum, chromium), which have relatively low potentials, have high corrosion resistance.

Chemical corrosion in its pure form is quite rare. An example of this is the appearance of scale during hot processing of metals. Atmospheric corrosion (outdoor corrosion) is a combined chemical and electrochemical corrosion.

Methods of corrosion protection

Steel and cast iron, which are the main part of all technical metals and alloys, rust quite a lot, so their protection against corrosion requires special attention. The production of corrosion-resistant alloys (for example, high-chromium and chromium-nickel steel) is in itself a way to combat corrosion, and the most effective. Stainless steels and cast irons, as well as corrosion-resistant alloys of non-ferrous metals, are the most valuable structural materials, but the use of such alloys is not always advisable due to their high cost or technical reasons.

Ways to protect metal products from corrosion:

1) metal coatings;
2) chemical coatings;
3) cathodic protection;
4) non-metallic coatings.

Metal coatings

Corrosion protection by applying a thin layer of metal, which has sufficient stability in this environment, gives good results and is quite common.

Metal coatings can be applied [78]:

– hot way;
– galvanic method;
– by diffusion method;
– thermomechanically;
– metallization (spraying), etc.

The hot method is used to apply a thin layer of refractory metals: tin (tinning), zinc (galvanizing) or lead (leading). In this method, the cleaned product is immersed in a bath of molten metal, as a result, the metal wets the product and deposited on it in a thin layer. Tinning is mainly used for utensils (boilers, pots, etc.); galvanizing – for household products, iron for roofs, wires, pipes; leading– for chemical equipment and pipes.

The galvanic method is to apply zinc, cadmium, tin, lead, nickel, chromium and other metals to the product. There are anode and cathode galvanic coatings.

The anode coating is made of metals, the potential of which in this electrolyte is lower than the metal potential of the product.

The cathode coating is carried out by metals whose potential in this electrolyte is higher than the potential of the parent metal. The cathode coating protects the base metal as long as it is solid.

To apply the coating, the product is immersed in an electrolytic bath with a solution of salts of the metal to be applied in the form of a protective layer. The product serves as a cathode, and as the anode use either a metal that does not dissolve in this electrolyte, or the metal that will be deposited.

The galvanic method is widely used because it allows the application of any metal on the product, allows you to accurately adjust the thickness of the protective metal layer and does not require heating the product. Galvanic coatings are applied not only to protect against corrosion, but also for [79]:

– increase of surface hardness and resistance to abrasion (chrome plating, nickel plating);

– improvement of the decorative appearance of the product (gilding, nickel plating, chrome plating);

– increase of their heat resistance (chrome plating);

– obtaining a surface with greater imprint (nickel plating followed by polishing, chrome plating), etc.

The diffusion method is to saturate the protective metal of the surface layer of the product. This saturation is carried out by diffusion at high temperatures (chemical-thermal treatment). In this way, alliteration (saturation with aluminum), chromium plating and silicification (saturation with silicon) are performed.

Thermomechanical coating (cladding) is to obtain bimetals (double metals) by compatible hot rolling of the base and protective metal. Coupling between metals is carried out by diffusion under the influence of pressure and high temperature. This method is the most reliable way to protect against corrosion. Steel is protected by copper, tompak, stainless steel, aluminum; duralumin clad with pure aluminum.

Metallization is carried out by spraying drops of molten protective metal on the surface of the product using a special device – a gun. The protective metal in the form of a wire is fed into a gun, where it is melted by an acetylene-oxygen flame or an electric arc and sprayed with an air stream. Metallization is convenient for protection of large products and implementation of unilateral coverings. Stainless steel and non-ferrous metals are used as protective metals during metallization.

Chemical coatings

The chemical coating is that on the surface of the product artificially create protective metal films, often oxide. The process of creating oxide films is called oxidation or blueing (due to the fact that after processing the product is blue-black). When oxidizing steel, the product is subject to oxidants. The most common is a method of immersing products in solutions of nitric acid salts at a temperature of about 140 ^{o}C. After oxidation to increase corrosion resistance, the product is usually coated with a fatty substance or mineral oils that fill the pores of the oxide film and prevent moisture from penetrating the metal [80].

To protect against corrosion, phosphating is also used, which consists in creating a film of phosphate salts of iron and manganese on the surface of the part.

Cathodic protection

Cathodic protection is used for products that work in electrolytes. The essence is that to the surface to be protected, or attached to it, protectors made of metal having a potential lower than the potential of the product to be protected. This produces a galvanic pair of product – tread, in which the anode will be the protector, and the cathode – the product. Under such conditions, the tread will gradually break down, thus protecting the product. After the destruction of the tread it is replaced by another [90].

Non-metallic coatings

Non-metallic coatings are coatings with paints, enamels, varnishes and lubricants. The role of paints, as a means of protection against corrosion, is to insulate the metal from the environment and prevent the activity of micro-elements on the surface of metals. Paints and varnishes are used quite often and account for about 70% of all cases of protection of metals from corrosion. Paints and varnishes reliably protect surfaces from corrosion in atmospheric conditions. The process of performing the coating operation is quite simple. The disadvantage is the fragility of the coatings and their burning at high temperatures.

Various mineral oils and fats are used as lubricants. Protection with lubricants is usually carried out during storage and transportation of metal products. Lubricants are periodically updated.

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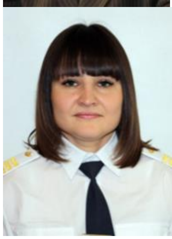

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