Information flows of parallel computing of the distributed control systems of aviation engines

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Abstract. The ongoing work on scientific and technical suggestions for 6th generation engines has been considered and the necessity for developing methods for constructing adaptive control of aircraft engines has been substantiated, which will allow, due to the flexible structure of the control system, to determine the number of adjustable parameters and the number of adjustable factors for the formation of engine control programs. The information flows of aircraft engine control systems have been analyzed using an example of a system with full responsibility of the FADEC type and a method for their parallel calculations is proposed, for the implementation of which it is necessary to develop a virtual channel model, a background stream generator, and a data parallelization method.

1. Introduction

The aviation engine (AE) is an important part of any aircraft, which determines its flight and technical characteristics, safety, reliability, economy, and cost of operation. Over more than 60 years of aircraft development with jet engines, five generations of aircraft engines have been created with a cardinal improvement in their performance, and aviation has become a major factor in the development of the world transport system and ensuring a country's defense capabilities. The improvement of aircraft engines was achieved due to the transition to new schemes, increasing the parameters of the cycle and the degree of double-loop, the introduction of new construction materials and technologies, improving automatic control systems of the gas turbine engine (ACS GTE).

From the beginning of the 1950s-1960s automatic control systems of the gas turbine engine used rather simple control algorithms, according to which in hydraulic and mechanical devices the rotor speed was regulated with the introduction of the necessary influences on the derivative and variable gain as elements of adaptation to the operating mode (isodrome regulators). Development of gas turbine engines with adjustable elements of the flowing part (compressor guide device, nozzle), with afterburner combustion chamber, with adjustable screw and increasing the level of working process parameters (temperature and gas pressure) has led to more complicated control tasks caused by interaction of control circuits. (construction of autonomous ACS, development of the theory of invariance) [1].

Further expansion of the scope of tasks, increasing engine requirements for the level of basic characteristics (specific parameters, reliability, resource) has led to more accurate monitoring of changing in-flight operating conditions, improving control accuracy in steady and transition modes to ensure the implementation of engine characteristics, laid down in its design, and increase the efficiency of the aircraft.

The solution to these problems became possible with the development of methods of adaptive and integrated control of the power plant (PP) [1,2], which allows by automatic control means to obtain the best characteristics of the engine and PP in general for specific flight conditions, for example: the best engine efficiency in cruising; high maneuverability of fighter aircraft; necessary reserves of gasdynamic stability (GDS) under the influence of strong disturbances (external and internal) and when flying at high altitudes, etc.
Since the early 2000s, there has been ongoing work towards creating scientific and technical suggestions for 6th generation engines and their control systems (VAATE, AETD, INVENT programs, etc.), the budget funding of which in recent years is 400-450 million dollars per year. The purpose of these programs is to develop highly efficient components, gas generators, engines, and systems for power plants of military and civilian aircraft with characteristics significantly exceeding the characteristics of 5th generation engines [1]. Based on the results of current projects, aircraft engine manufacturers have begun work on 6th generation engines (maximally integrated with the aircraft), the commissioning of which is expected no earlier than 2025. The technologies used in them will be directed not only to increase the parameters of the working process and improve the weight efficiency of the structure, but also to reduce all components of the cost of the life cycle of the engine [1,2].

A study on engines by Boeing, General Electric, Nortrop Grumman, Pratt & Whitney and Rolls Royce [2] showed that the creation of an adaptive three-circuit engine will significantly improve fuel efficiency, reliability and flight safety.

Research on developing methods for building adaptive control of aircraft gas turbine engines will allow - due to the flexible, easily changeable structure (information flows) of the control system - to determine the number of controllable parameters and the number of controllable factors, which in turn are a set of control programs and depend on engine performance requirements.

2. Electronic ACS with full responsibility

The main requirement for electronic automatic control systems of the gas turbine engine is the requirement of high reliability and performance of system elements in a wide range of changes in operating conditions. The importance of the problem of ensuring the reliability of automatic control systems of the gas turbine engine is explained by the increased impact of failures of the control system on the operation of the power plant. Thus, the analysis of statistical data conducted by foreign companies [2,3] indicates that approximately 30% of aircraft accidents with gas turbine engines occur due to failures of control systems.

Ensuring the required level of reliability of electronic automatic control systems of the gas turbine engine should be observed at all stages, from the beginning design to commissioning. Along with the known methods of increasing reliability such as reducing the failure rate of ACS elements, direct reservation of the main electronic units and the use of reserve hydromechanical automatic control system, algorithmic methods to increase reliability are becoming more common [3]. Such methods involve the synthesis of a control algorithm that ensures the normal functioning of the system not only in good condition, but also in the event of the failure of a number of subsystems.

Another aspect of the problem of ensuring the reliability of electronic automatic control systems of the gas turbine engine is related to the organization of the control process, in which the failure of individual subsystems will not lead to the failure of the entire system. This can be achieved by properly distributing the functions between the subsystems and providing the conditions under which the control subsystems will be able to take over the functions of the failed subsystems.

The main disadvantage of modern electronic automatic control systems is their low reliability. However, in the future, as experience operating such systems increases and with the modernization of the element base, the reliability of these systems will increase.

If the FADEC type ACS fails, the possibility of direct engine control is excluded. They use two or more independent control channels with their own power supplies, sensor-to-sensor converters, built-in control system, memory, etc. for reserve purposes. The use of ACS with full responsibility provides cost reduction not only to organizations’ engine operators, but also to developers of gas turbine engines (GTE). Such systems are simpler and lighter than hydromechanical ones. They can be modified and improved throughout the life cycle of the engine.

Modernization of the hydromechanical system is a very expensive process [2,3], and can only be justified by a significant improvement in engine performance. In the study of engines to improve their performance and technical characteristics, as a rule, changing the equipment of the ACS is not
required, and only the software is changed. This allows us to explore any improvements in engine performance, no matter how small.

As practice shows \cite{3}, minor software changes in the control system can be made directly on the stand from 1 to 2 days during the test, and more significant changes, associated with the introduction of additional measurement channels, control of additional actuators (A), i.e. require hardware refinement of units for 2-3 weeks. Electronic FADEC type ACSs can significantly reduce the test program of the engine and aircraft.

Due to increased competition in the field of aircraft construction, the time for the development of ACS is significantly reduced. If in the 90s they could be developed for the AN-70 aircraft in 3 to 5 years, today the development, commissioning and refinement of AN-148 aircraft systems is supposed to only take 2 to 3 years.

The purpose of the development of the Antonov Enterprise is to produce a competitive version of the AN-158 aircraft meeting the latest European standards. The time allotted for the development and construction of the aircraft itself, as well as this complex of onboard avionics, the development specifically for this aircraft APP MS2 with its ACS, a deep modification of the ACS MPP (almost a new development) and conducting tests is only 1.5-2 years. Customers of ACS (Enterprise "Progress" and Enterprise "Motor-Sich") are constantly tightening the requirements for accuracy, sensitivity, noise immunity and speed of calculation of measuring channels.

All of this is happening against the background of a constantly growing number of orders for the development and modernization of existing control systems and diagnostics of aircraft engines. Given the current situation, a typical functional scheme has been developed, on the basis of which control systems and engine control systems are built, using well-proven circuit solutions previously used in developments on modern aircraft, which are successfully operated at the moment.

A typical block diagram of an electronic ACS with full responsibility is shown in ‘Figure 1’.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure1.png}
\caption{Block diagram of electronic ACS with full responsibility}
\end{figure}
Tasks solved by the ACS can be conditionally divided into three great classes [1-3].

1st class:
- collection and processing of information from analog sensors and discrete alarms;
- filtering from faulty values, rattling of contacts, etc;
- reduction of the measured electric value of the parameter to a physical quantity by means of interpolation formulas and admissible control of the received values;
- control of the integrity of the communication line with sensors and alarms;
- internal control of serviceability of conversion and measurement channels.

2nd class:
- solution of engine control and monitoring algorithms.

3rd class:
- formation of commands of management of executive mechanisms, definition of serviceability of actuators and integrity of lines of communication with them;
- exchange through information exchange channels with interacting systems.

There are a number of less important tasks, such as "service" functions of ACS, which can be solved in the background on the remaining CPU or allocated to individual single-channel devices, such as built-in drive, counting engine and ACS, number of starts and time of rotors, electronic engine passport, etc.

In the considered model of ACS it is proposed to develop two types of target processor devices. The first type is to solve collection problems (1st class of tasks), the second is to implement control and exchange functions (3rd class of tasks).

After estimating the amount of resources involved on the target microprocessors consider the following points: the problem of solving algorithms to solve on a freer computer or distribute them between computers so as to minimize interprocessor exchange on the internal bus.

For example, the system OnBCVS-436 (on-board control and vibration system of the engine D-436 aircraft AN-148) must provide simultaneous reception information from three systems: BPK-148, ECS-436, BKR-436 on the ARINC-429 channel at a frequency of 100 kHz and pauses between parcels 4-8 T (almost full bus traffic) and itself must issue information also at a frequency of 100 kHz with pause 4-6 T.

This means that an interrupt service request from RZ receivers will occur almost every 80 μs (one interrupt processing time from 6 to 10 μs). At such a "torn" mode of operation of the processor it is impossible to speak about the parallel decision of algorithms of control of the engine. Therefore, tasks of collecting and processing of algorithms of control of the engine solve by means of the device of collecting and processing of information (CPD), and the device of the central computer (CCD) in the implementation of OnBCVS-436 performs the function of a communication processor and solves all "service" problems [3].

On the contrary, in the control and monitoring unit of APP MS2 - BPK-MS2 the scope of tasks of collecting and processing information is significant. The unit receives information from 12 analog sensors by each CPD channel. To ensure the quality of control, some parameters are measured with a frequency of 100 Hz (taking into account mathematical filtering), and the parameters involved in the surge protection algorithms are calculated with a frequency of up to 200 Hz. Given that the scope of tasks of forming control commands and external exchange is relatively small, the solution of control algorithms and control of fuel consumption and control of the compressor is implemented on the CCD device.

Thus, the proposed structural scheme of the ACS for the implementation of the above tasks is very flexible. Consider briefly the main functional units of the ACS.

**CPD** is a device for collecting and processing information, designed to solve the following main tasks:
- 1) collection of information from analog sensors;
- 2) power supply of analog sensors;
3) filtering of measurement results from faulty values;
4) tolerance control of measurement results;
5) time averaging of measurement results;
6) reduction of measurement results to physical quantities;
7) determining the integrity of communication lines with sensors (short circuit / break);
8) determining the serviceability of the internal stages of conversion of sensor signals;
9) issuance of information to the CCD device in accordance with the internal exchange protocol.

The structure of the CPD device can be quite diverse for different implementations. For example, in the BPK-MS2 unit, in addition to a powerful 16-bit target computer with CICS architecture, the CPD includes several "fast" 8-bit microcontrollers that solve local problems with high frequency.

**CCD** is a device of the central computer, designed to solve the following main tasks:
1) formation of discrete control commands of the engine actuators (ignition units, starter, air intake, air intake valve, fire hydrant, etc.);
2) formation of analog commands to control the engine actuator (fuel consumption, inlet guide device, service compressor, air bypass valve, etc.);
3) information interaction on the ARINC-429 channel;
4) determining the serviceability of its own circuits and devices of the unit;
5) control of inconsistency of the parameters received on the internal channel of interboard exchange from CPD devices.

**SD-MS2** is switching device, the main functions of which are:
1) determining the serviceability of the devices CCD-1 and CCD-2 and switching to the outputs of the circuit from the serviceable channel;
2) conversion (amplification) of control commands from CMOS levels at the level of +27 V / Housing;
3) conversion of analog commands to the type required for the actuator.
The **SD** device includes:
- automatic engine power turbine protection (AEPTP), which is an independent device that has its own power supply;
- "dedicated" speed sensors.

A minimum number of connections is used to connect to other devices of the unit, which reliably ensures an emergency stop of the engine when the rotor speed of the power turbine exceeds a critical value (i.e., if the AEPTP started and turned off the engine, then the unit is inoperable).

**SD** is the device of the built-in operational drive. Is an auxiliary device that performs service functions. It is installed in the products if necessary. Main tasks:
1) implements the functions of the built-in operational drive of the unit;
2) performs the functions of the implementation of the resource counter, operating time, rotor run time, start counter or engine cycles, etc.

The device can be used as a powerful coprocessor to solve capacious computational problems such as "Fourier transform", as well as in a system where a large amount of intermediate mathematical calculations is required.

**PS** is power supply device. This is a two-channel device that operates in the range of supply voltages from +10 to +36 V. It carries out filtering of supply voltage emissions above 42 V and generates secondary voltage sources +5 V (1.5 A), +15 V (0.5A), - 15 V (0.5 A). At a long excess of the specified currents, protection defines a situation FAILURE OF THE CONSUMER, forms a signal +27 V is the CHANNEL OFF and disconnects the consumer in the trigger mode.

Consider the scheme of information flows within the ACS, shown in ‘Figure 2’. One of the bottlenecks of electronic ACS is the internal channel of inter-exchange exchange (hereinafter - IECH). If you implement a two-channel ACS with one internal channel IECH, then automatically from the name of such a system it is necessary to exclude the word "two-channel", you get a "conditionally reserved" system.
The physical interface through which the internal IECH is implemented is not so important. Microprocessors often use built-in serial communication channels (SPI, UART, I2C, etc.), use a parallel bus (I41, ISA) or implement an internal IECH based on standard on-board interfaces (ARINC-429, MIL-STD-1533).

In digital transmission of continuous messages, the interference in the channel leads to the fact that instead of the transmitted code combination, which corresponds to the quantized count of the message \( y_i \), another code combination corresponding to the quantization level \( y_j \) is received, i.e. there is an anomalous error. Its significance \( \varepsilon_{an} = y_i - y_j \).

The reliability of the transmission of continuous messages in digital systems is usually characterized either by the probability of anomalous errors \( P_{an} \), or the reduced standard error \( \delta_{an} \) due to the action of anomalous errors. The value of possible reception error depends on the type of channel, physical interface and probability of error when receiving a symbol. Thus, when choosing an exchange channel it is necessary to take into account the probability of receiving/transmitting information and develop algorithmic methods to detect and parry failures without losing system quality.

For example, the SPI interface is used as an IECH for the BCHB-1 hydraulic brake control unit. The exchange protocol is developed, considers formation of the checksum, parity bits, frame number, the selected exchange rate considering 30\% of the traffic reservation [3].

However, the BCHB-1 unit is a bench equipment and such a solution is unacceptable for onboard systems, because the physical interface of the SPI channel is implemented as a single-wire unipolar line of communication CMOP levels of low reliability with fast transmission of information by serial parcels.

In each case, it is necessary to calculate the traffic of the internal IECH, consider the issues of reliability and noise immunity, develop error detection algorithms, and calculate the time of parrying the error.
When conducting factory tests of the unit it is necessary to test the susceptibility of the exchange channel to external electromagnetic interference, and test for the formation of external electromagnetic influences of the unit with different modes of internal IECH (maximum traffic at the cutoff frequency, regular traffic at sufficient exchange rate 50% reserve).

For example, during factory tests [3] of the BFM-140 unit (fuel measurement system of the AN-140 aircraft) the excess of electromagnetic interference generated by the unit was detected. As a result of the analysis and experiments, it was found that the internal parallel bus I41 “foning” due to the use of too powerful tire drivers and an incorrectly calculated load.

The system built on the given structural scheme has good indicators of functional reliability, and easily adapts to constantly adjusting requirements to computational algorithms.

Using a unified scheme, it is possible to conduct parallel development of systems similar in class to the problems to be solved. The main forces of the developers will be focused on the careful development of algorithms, allocating minimal financial resources and labor resources for hardware development.

According to the above and considered structural scheme, systems BCDS-27M (the modernized control system of the D-27 engine), BCVS-436 (onboard system of control of the engine and control of vibration of the D-436 engine), BCVS-18 (onboard system of control of vibration of the engine D-18), BCM-MS2 (control and monitoring unit of APP MS2) have been developed [1-3].

3. Engine communication structure

The problem of processing the large flows of heterogeneous information is currently decisive in the development of systems that accompany the life cycle of the engine (LCE). The size of information flows depends on the complexity of the detail or node, the accuracy of calculation schemes and models, as well as the accepted in the systems of design and mathematical modeling formats of data presentation and storage. The integration of mathematical modeling and design systems implies the presence of powerful computer technology with large Random Access Memory (RAM) and disk space. All systems on such computers must meet a level of reliability that would provide almost 100% security against losses during storage, transmission, and processing of information, as well as when switching to new computers and operating systems.

If one considers a typical node of the supergraph of the design process, the compressor node (‘Figure 3’), then it should be noted that it contains both a subset of internal connections and relations describing interaction with other objects (nodes) of the design. Obviously, software designed to control the flow of information in such complex processes as creating and maintaining an informational layout of the engine design process should have sufficient flexibility and be able to automatically establish or break connections between objects (nodes of the design supergraph).

![Figure 3. Internal structure of information connections in the compressor node](image-url)
In many ways, this process resembles computer simulation of neural networks. Connections in these networks should be formulated in accordance with the principles of organizing relations in systems of structural analysis. The technical solution to this issue lies in the development and implementation of software and CALS technology tools, while some success can be achieved through the use of parallel designing (computing) of engine information systems.

3.1. Parallel computing

The organization of parallel computing on multiprocessor systems requires the use of special programming techniques, which leads to the high complexity of writing programs. In addition, there are problems with portability of programs, since any program for parallel machines is closely related to the architecture of the computer on which it is implemented [4].

To implement the program algorithm on a parallel system, the algorithm is represented in the form of sequentially performed ensembles of operations, and in each ensemble all operations are not connected to each other. If the architecture of the parallel system allows to realize simultaneously all the operations of each ensemble, then without taking into account the time for data transfer, the execution time of the algorithm will be proportional to the number of ensembles. The number of ensembles is called the height of the algorithm. Algorithms in which the height is less than the total number of operations are called parallel, and their representation through a sequence of ensembles of independent operations is called parallel form. Depending on the structure of relations between operations, the same algorithm can be represented in various ways as a set of ensembles. In particular, the usual sequential implementation means that each ensemble contains only one operation. For most algorithms, there can be many such representations. Finding algorithms of minimum height is of particular interest for each task.

Let us consider an example, quite often cited as an illustration of parallel algorithms [4], in which the idea of constructing low-height algorithms is clearly visible.

Suppose that it is required to calculate the product of $n$ numbers $a_1, a_2, \ldots, a_n$, and let us set $n = 8$. The usual scheme that implements the process of sequential multiplication is as follows:

Data $a_1 a_2 a_3 a_4 a_5 a_6 a_7 a_8$

Layer 1 $a_1 a_2$
Layer 2 $(a_1 a_2) a_3$
Layer 3 $(a_1 a_2 a_3) a_4$
Layer 4 $(a_1 a_2 a_3 a_4) a_5$
Layer 5 $(a_1 a_2 a_3 a_4 a_5) a_6$
Layer 6 $(a_1 a_2 a_3 a_4 a_5 a_6) a_7$
Layer 7 $(a_1 a_2 a_3 a_4 a_5 a_6 a_7) a_8$

The height of the parallel form is 7, the width is 1. All the factors must be divided into pairs, and two numbers are multiplied inside each pair. All these operations are independent. Obtained partial products also must be divided into pairs and again two numbers are multiplied inside each pair. Again, all operations are independent.

Data $a_1 a_2 a_3 a_4 a_5 a_6 a_7 a_8$

Layer 1 $a_1 a_2 a_3 a_4 a_5 a_6 a_7 a_8$
Layer 2 $(a_1 a_2)(a_3 a_4) (a_5 a_6)(a_7 a_8)$
Layer 3 $(a_1 a_2 a_3 a_4) (a_5 a_6)(a_7 a_8)$
The height of the parallel form is 3, the width is 4. The desired product is obtained through $\log_2 n$ steps. At the first time step $n/2$ processors can be used, at the second $n/4$, etc. This algorithm is called the doubling process. On the ‘Figure 4’, graphs of sequential and parallel algorithms are presented.

Solving the task of parallel computing (designing) in the information structure of aviation engine distributed control systems formed a new field of research called the informational structure of algorithms [4,5], within the framework of which theoretical and practical results can be obtained, and many problems can be solved on adapting serial programs to the requirements of parallel architecture computers.

3.1.1. Method of parallel computing of distributed control systems of aircraft engines

The model of information flows of parallel calculations of distributed control systems of aircraft engines is a virtual channel (VC) in the form of a route in the network from the source node to the destination node, consisting of a sequence of switching nodes transaction processing and communication channels between neighboring nodes. The same VC model for the representation of different classes differs only in parameters. To account for the influence of flows circulating on the network and being background, the probable equivalent of the unconsidered part of the network in the form of a background flow generator is constructed in the selected VC, which takes into account the interdependence of parameters and processes of the whole network [4,5]. The structure of the VC model is shown in ‘Figure 5’.
The structure of the method fits well with the parallel computing paradigm SPMD (Single Program - Multiple Data), which allows you to organize distributed simulation modeling of aircraft engine control systems according to the proposed method on multiprocessor computing systems: as copies of programs hosted on different processors, a virtual channel simulation model is used; distributed portions of data processed by the program are classes of transaction transportation paths; Synchronization of interacting processes is performed by the background thread generator, which takes into account the mutual influence of the processes occurring in the simulated system on the functioning of the selected transaction transportation paths.

The background flow generator replaces the synchronization algorithm for the interaction of system processes and is a kind of analogue of the distributed process synchronization algorithms in MPMD (Multiple Program - Multiple Data) - modeling of aircraft engine control systems.

4. Conclusion

The analysis of the subject area "aviation engine" and its control system have been considered, the main technologies for the development of an aircraft engine (5th and 6th generation) have been determined, and the need for building adaptive ACS has been proposed.

The architectures of the main information and control systems, the model of sensors and the typical structure of electronic ACS with full responsibility have been determined, as well as its tasks: information collection and processing, filtering, reduction of parameter values to physical quantity, control of communication lines integrity, internal control of conversion channels and measurement, solution of algorithms of management and control of the engine, formation of commands of management of executive mechanisms; exchange through information exchange channels. The main functional units of ACS have been analyzed.

Currently, the control system of aircraft and aviation engines is characterized by the following main features [1-5]:

- the architectural construction of the control system involves the use of digital computers with heterogeneous redundancy, digital information systems of motion parameters, side handles or mini-steering wheels as control levers and electro-hydraulic drives for rejecting the main controls;
- algorithmic support of control systems involves a wide adjustment of control coefficients according to flight parameters to ensure optimal control characteristics, auto-balancing, counteracting disturbances and implementing warning and limiting functions such as the angle of attack, normal overload, instrument speed and Mach number, pitch and roll angles.

A parallel computing method for distributed control systems of aircraft engines has been proposed, in which it becomes possible to place the same simulation program on different processors of the computing system, and all programs will work in parallel, but each with its own data area. Upon completion of the programs, the results are transmitted through the transmission medium to the results processing module, where the sought probability-time characteristics are calculated in accordance with the layered sampling method.

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