Modernizing complexes of scale and semi-scale simulation of disturbed flight

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Abstract

This paper deals with solving the problem of modernization of complex scale and semi-scale simulation of disturbed flight. The main goal of the research is to ensure the maximal proximity of imitation of real flights. Methods of ensuring the adequacy of dynamic models of the simulator and simulated model for scale simulation of flights are proposed. The structural diagram of the "flying model" with the corrected dynamics is represented. New technologies to ensure the adequacy of dynamics models of the simulator and simulated object are represented. Structural diagrams of automated complexes of semi-scale simulation of flight have been analyzed. The structural scheme of the modernized complex of semi-scale simulation is developed.

Keywords

disturbed flight, natural and semi-natural modeling, adequacy of models, multi-dimensional stand

1. Introduction

Among the many problems, for example [1, 2, 3], the creation of full-scale and semi-realistic flight simulation complexes, as well as the related problems of creating mobile aviation simulators, we will discuss one of the problems that arose at the current stage of the development of these fields of science and technology such as the problem of optimal modernization of stochastic turbulent flight simulation complexes. This problem arises during the creation, operation, and modernization of existing mobile complexes of full-scale and semi-full-scale flight simulation of objects for various purposes. One of the main tasks in this case is to ensure the maximum closeness of the simulated and real flights [4, 5, 6].

The scientific and technical difficulties of solving this problem are primarily related to the nature of the dynamics of the control process, simulating the moving object, and the nature of the dynamics of the multidimensional simulator used in modeling as the basic part

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of all mobile flight simulation complexes. In automatic complexes, the main aspect of the quality of imitation is accuracy, and the choice of control of the imitation complex should be made with the condition of achieving the highest quality of imitation. A significant complication of the problems of improving the accuracy of simulation complexes control in comparison with the same problems of flight control is associated with the introduction of an additional unit into the control loop – "the flying model" of the simulator stand, which has complex dynamics.

In mobile aviation simulators, which are mainly intended for pilot training and skills in solving special flight tasks by operators, additional problems arise related to the reliability of the occurrence of acceleration sensations similar to those occurring in real situations in pilots who are learning to control flight in ground conditions.

The formulated problem is considered only for automatic modeling complexes, but according to the results of robots related to the activities of pilots and operators in stochastic conditions close to flight conditions, it could be extended to semi-automatic modeling complexes [7, 8, 9].

We will assume that the statement of the problem of maximizing the accuracy of simulation in automatic flight dynamics modeling complexes is determined by two main circumstances. Firstly, there are significant differences between the dynamics of the "flying model" during full-scale simulation and the dynamics of the flight simulation system on the "computer-dynamic stand" during semi-realistic simulation from the dynamic characteristics of the simulated moving object. This circumstance in some cases can lead to the impossibility of flight simulation in stochastic ground conditions. Secondly, in situations where the "adequacy" of the dynamics of the object and its imitator is achieved in the specified manner, the maximization of the accuracy of the imitation is associated with the choice of the optimal motion control system of the adjusted "flying model" or imitator in full-scale and semi-full-scale simulation complexes, taking into account stochastic flight factors. It is believed [10, 11] that the formulated accuracy problem of flight simulation can be solved in different ways, which are described below.

2. Development of methods for ensuring the adequacy of dynamic models of simulator and simulated object during full-scale flight imitation

Currently, full-scale simulation of the flight of an object that is just being developed or modernized is performed directly during the flight of some aircraft, the systems of which allow some restructuring of parameters or structure. The structure of such a simulated flight control does not differ from the usual one. When the adjustment limits of the flight control system of the "flying model", which simultaneously performs the functions of flight control and correction of the dynamics of the "flying model", are not enough to achieve the goals of simulation, then an electronic model of the dynamics of the object being developed can be put on board. In this model, if possible, influences, controlling, and perturbing, which take place in flight, are taken into consideration. The result of comparing the state vectors of the "flying" and "electronic" models must be used in a certain way to correct the dynamics of the "flying model". Such approaches have some points that certainly reduce the quality of modeling [12, 13, 14].

There is another way to solve the problems of full-scale simulation, which is based on well-known [15] algorithms of synthesis, identification, observation, and analysis of stochastic stabilization systems and consists of some research phases. In the first phase, the structural identification [16, 17] of the "flying model" is carried out in the specified flight modes. Then the dynamic certification [2] of on-board meters is performed, and models of disturbance dynamics in the studied operating modes are determined. The collected information of the second phase to carry out the dynamic design [18] of the system for correcting the dynamics of the "flying model" to the dynamics of the object under study. This phase is performed based on algorithms for the synthesis of closed stochastic stabilization systems. The "flying model" in conjunction with the received dynamics correction system creates the internal circuit of the flight control system of the "flying model" and will be the closest model of the object under study (Figure 1). The external control loops of the adjusted "flying model" can also be synthesized in the process of dynamic design and implemented before the start of full-scale modeling. Even with significant differences between the a priori accepted models of links and signals from real flight ones, the synthesized correction and control systems will be minimax. As input models for dynamic design will improve, their results will approach the best ones [19, 20].

If it is necessary to adaptively adjust the parameters of the selected "flying model" correction system in real flight with the help of a synthesized observation system. It is possible to estimate the state of the model in each specific flight mode, compare it with the one programmed in this mode and embedded in the memory of the computer on the "flying model" and, based on the results of the comparison, generate control signals for the contour of the adaptive setting of parameters.

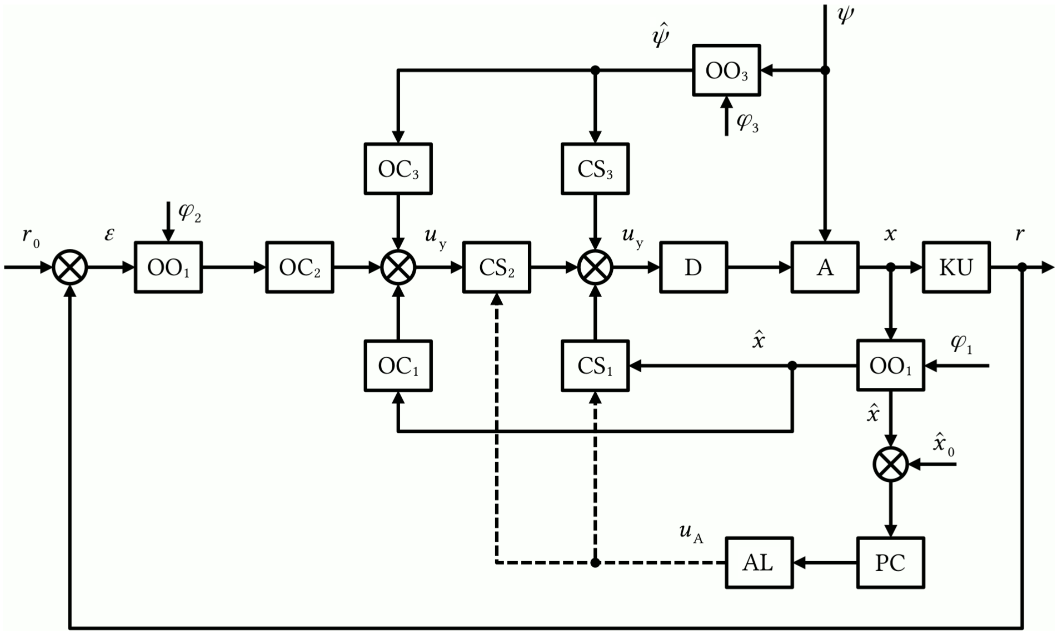

Figure 1: Structural diagram of the optimal control system.

Figure 1 shows the structural diagram of the optimal control system of the "flying model" with adjusted dynamics. The "flying model" dynamics correction system consists of parts of this system CS_1, CS_2, and CS_3, which use estimates of the state vectors of the model $\widehat{x}$ and perturbations $\widehat{\psi}$ in conjunction with an a priori estimate of the control signal U_y, which is transformed in the CS_2, creating a signal of the internal control loop system CS_2 – drive D – "aircraft flying model". External stabilizing circuits relative to the created model create an optimal autopilot (part of the controller) (OC_1) and an optimal correction system in the disturbance circuit (OC_3, OC_3). The outer (navigational) circuit includes the optimal structure (OC_2) that makes up the trajectory control system as constituent parts. OO_1, OO_2, and OO_3 are parts of the optimal observer; OC_1, OC_2, and OC_3 are parts of the optimal regulator; KU is the block of kinematic units; φ_1, φ_2, φ_3 are vectors of measurement disturbances; r_0 is a vector of the deterministic flight program signal; r is the vector of the completed flight program signal; and $\widehat{x}_0$ and $\widehat{x}$ vectors of the desired and implemented state signals of the aircraft; ε is the vector of error signals in the estimation of aircraft (A) states.

Based on the results of comparing the vectors $\widehat{x}$ and $\widehat{x}_0$, a vector ε is chosen, which can be used to generate adaptation control signals U_A in the personal computer (PC) software and the adaptation loop (AL), which will be able to change the set parameters in the CS_1 and CS_2 blocks. In some cases, it is possible to exclude contours of correction by disturbance.

When drawing up the structural diagram (Figure 1), it was considered that the main task of the specified version of the full-scale simulation is, for example, ensuring and evaluating the effectiveness of the optimal flight control system (OC_1, OC_2, OC_3). Scale simulation can have other goals and objectives.

3. Development of technologies to ensure the "adequacy" of simulator and object dynamics models during semi-scale flight simulation

In automatic systems of full-scale simulation, as well as in moving aviation simulators, we consider the main goal of simulator dynamics correction to be the most complete elimination of the influence of the dynamics of the stand that simulate movement, as a dynamic unit that does not exist in real-time flight control loops [21, 22, 23].

We will briefly describe the widespread options for creating such complexes and simulators. For certainty, we believe that the main task of the simulation complex (flight simulator) in the first version of the design (Figure 2) is to assess the accuracy of the functioning of a certain functional complex in conditions close to a specific flight (to simulate the acceleration of the pilot's sensations, close to natural ones). In Figure 2, the following designations are adopted: FS is a closed static (computer-based) flight simulator that operates on program signals r, disturbances ψ, and measurement noise φ provides an assessment of the state of the object $\widehat{x}$ for a specific operating mode; SF is a system of filters designed to improve the dynamics of the simulation path or to smooth out the difference in the accelerations of the pilot's sensations during their ground and field studies;

MS is a closed mobility system that has internal disturbances η and is designed to convert signals $\hat{x}$ into mechanical signals $\hat{x}_M$ with dynamic characteristics closest to the state vector $\hat{x}$; RO is a researched object exposed to the action of internal disturbances ξ, the assessment of its state $\hat{y}$ and accuracy of functioning are the goals of the research.

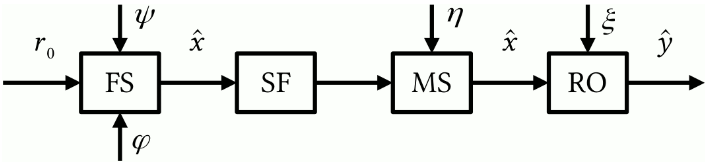

Figure 2: Structural diagrams of an open automatic complex of semi-realistic flight simulation.

The positive feature of such a structure of the complex is the comparative simplicity of the design and configuration. The essential disadvantages are the same as the impossibility of generating signals $\hat{x}_M$ close to the signals $\hat{x}$ due to inertia, the limited bandwidth of passing the frequencies of the reference signals through the mobility system, and, as a consequence, the insufficient correspondence of the achievable state $\hat{y}$ to the actual value. As a result, it is impossible to obtain reliable accuracy estimates for research object, which has high accuracy requirements [24, 25].

The variant of the modeling complex, the structural diagram of which is given in Figure 3, is usually used to estimate the quality of the real flight control system. Here, a closed mobility system (spatial motion generator) is placed in feedback to the object (the model of the aircraft), which is subjected to external disturbances ψ and has a state of $\hat{x}$. This system includes real airborne measuring instruments (AMI) that generate signals for the aircraft control system (ACS). The mobility system consists of a multidimensional dynamic stand (DS) subjected to internal disturbances η and covered by feedback CS (control system) of stand motion with measurement disturbances ζ. The state vector of the mobility system $\hat{x}_M$ should be as close as possible to the state model $\hat{x}$. In the system of measuring instruments, there are measuring noise φ, in control systems - external disturbances ξ. The simulation complex reproduces the program movement r_0 and the vector of control signals denoted as u.

Here, the elimination of the negative influence on the dynamics of the mobility system is carried out by the possible expansion of frequency bandwidth. Such an approach is associated with carrying out expensive procedures, which, however, does not lead to an effective solution to the problem [26, 27].

A significant drawback of this modeling option is the weak consideration of external and internal stochastic factors influencing the control results, which requires setting up and solving other additional problems. Degradation in the quality of modeling is also associated with imperfect knowledge of the dynamics of multidimensional mobility systems, failure to perform complex algorithms for dynamic attestation of on-board meters, and so on.

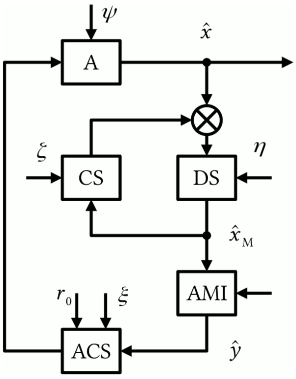

Figure 3: Structural diagrams of a close automatic complex of semi-realistic flight simulation.

4. Problematic issues in the modernization of highly effective complexes of semi-scale simulation for dynamic attestation of measuring instruments

To create or modernize moving objects that are highly efficient under stochastic conditions of operation, we also consider it expedient to carry out work related to the maximum mitigation of the harmful influence of mobility dynamics in modeling complexes. The successful solution to such a problem is based on the following circumstances. First, it is necessary to deviate from the traditional principle of building a complex, when the dynamics of a moving object (aircraft) are completely created by its model on a computer, and the mobility system plays the role of only a mechanical converter of the assessment vector of the aircraft model $\hat{x}$ into a state vector of the mobility system, and such a transformation is not suitable for current modeling requirements. Secondly, as a basic dynamic object, it is expedient to adopt the multidimensional stand-simulator of spatial movements itself, to adjust the dynamics of the stand to the dynamics of the simulated aircraft using a special synthesizable optimal correction, which is implemented based on the results of optimal synthesis on a computer. The structural diagram of the semi-scale simulation complex modernized in the specified way is represented in Figure 4.

In Figure 4, the following designations are used: AMI is an airborne measuring instrument; DS is dynamic stand; DS is drive system; CS1 and CS2 are optimal control systems for determining the dynamics models of airborne measuring instruments and measuring noise; G1, G2 generators for the appropriate identification modes; MS is measuring system of the stand; FF is forming filter; OOS is the optimal observer of the state of the stand; CC is coordinate converter; SEQSM is a system for assessment the quality of imitation of stand movements; $\mathbf{y}$ is dynamic stand state vector; $\hat{\mathbf{y}}$ is a vector of the observed state of the stand; $\mathbf{x}$ is a vector of the true state of the on-board meter; $\mathbf{z}$ is a vector of the registered state of the on-board meter; $\hat{\mathbf{z}}$ s estimation of the state vector of the measuring instruments; $\hat{\mathbf{r}}$ is a vector of program signals; $\mathbf{f}$ – is stand disturbance vector; φ_c is a vector of the noise of stand measuring instruments; φ is noise vector of the airborne measuring instruments; $\hat{\varphi}$ is the assessment of the state vector of airborne measuring instruments; $\hat{\varepsilon}$ is an error of imitation of stand movements.

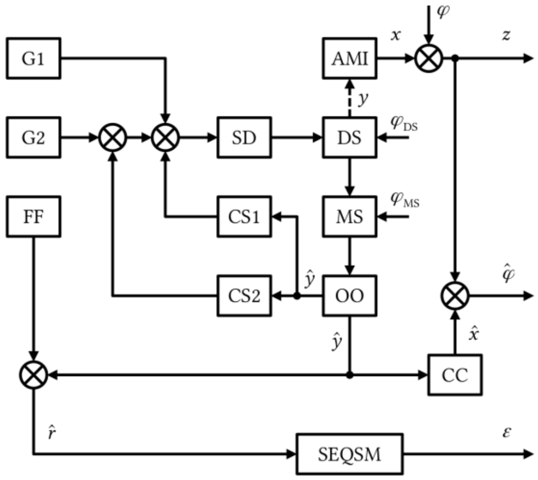

Figure 4: Structural diagram of the modernized semi-scale simulation complex.

5. Dynamic attestation of measuring instruments

The accuracy of on-board meters depends on the design quality and features, but also on the nature of the flight mode, the features of the operating disturbances, and noises that arise under specific operating conditions. As a rule, on-board meters are complex dynamic systems and operate under conditions of stochastic disturbances. The main disturbing factors include rotation of the aircraft relative to the center of mass, linear overloads of the center of mass of the aircraft during its movement along the flight path, vibration and shock overloads, moments of frictional forces in the axes of the suspensions of platforms and devices [28, 29]. The success of ground tests of onboard meters depends significantly on the presence of:

1. Test equipment capable of simulating real dynamic flight conditions;
2. Methods of certification of complex on-board measuring systems;
3. Information about real disturbing factors of flight.

Until now, in many cases, on-board meters for flight tests are certified in static conditions or with the help of special dynamic stands, when reproducing the movement of which the characteristics of the disturbed movement of the aircraft are not taken into account. But to evaluate the characteristics of an onboard meter taking into account external influences, it is necessary to know the dynamic characteristics of both the meter itself and its noises. Such opportunities are provided by the dynamic certification procedure.

The dynamic certification of an on-board meter is understood as the process of determining its transmission functions using a test bench that simulates the movement of an aircraft in a given flight mode [30, 31, 32]. The efficiency of the certification is caused by the following factors. Based on the principle of operation of most electro-mechanical units, such as gyroscopes, the noise of the meters is correlated with the movement of the base.

Determining the transfer functions of a one-dimensional meter does not cause complications and can be implemented by the technique of logarithmic magnitude-frequency responses using a test stand that simulates harmonic movements. Defining the dynamic model of a multidimensional gauge is a more complex process. For this procedure, you must have:

1. Multi-stage test stand capable of simulating a specified spatially disturbed movement of an aircraft;
2. Algorithms and methods of testing multidimensional onboard meters.

The problem of determining models of on-board meter noise, which are necessary for optimizing the accuracy of aircraft control, is particularly difficult [33, 34, 35]. This difficulty is caused by the following factors. The motion of the bench must reproduce a multi-dimensional stochastic process with given characteristics. To ensure the possibility of reproducing such a movement, it is necessary to create a complex dynamic certification, which should include a stand generator of specified movements and a stand control system. The creation of a stand management system is based on optimal synthesis algorithms [32, 33]. Such a system should provide:

1. Optimal assessment of the state of the tested meter.
2. Optimal assessment of the condition of the test bench.
3. Transformation of the measured state parameters of the tested bench into some reference frame related to the tested measuring instrument.
4. Comparative assessment of the state of the stand and the state of the tested meter and developing models of measuring noise.

The finite definition of measuring noise models of on-board meters is carried out with the help of statistical processing of test results and approximation of the obtained experimental dependencies with analytical formulas.

It will be noticed that the same tested stand can be used to determine the dynamics models of the on-board meters themselves and the noises to their measurements. At the same time, the stand management system must be renewed in correspondence with the solved problem.

The block diagram of the system for dynamic certification of airborne measuring instruments is shown in Figure 5.

Here, the stand of motion simulation (SMS) with internal disturbances and the optimal dynamics correction system jointly make up the model of simulating aircraft, and the correction system (CS) has two parts CS_1 and CS_2. Information about the state of the model x is provided by the optimal observer OO (the noise of state measurements). The system of airborne measuring instruments (AMI) with the noise vector φ supplies information to the real control system of the aircraft (RCSA), which generates the control vector of the model u . The RCSA block, which has its disturbance ξ , must receive a vector of program signals r_0 .

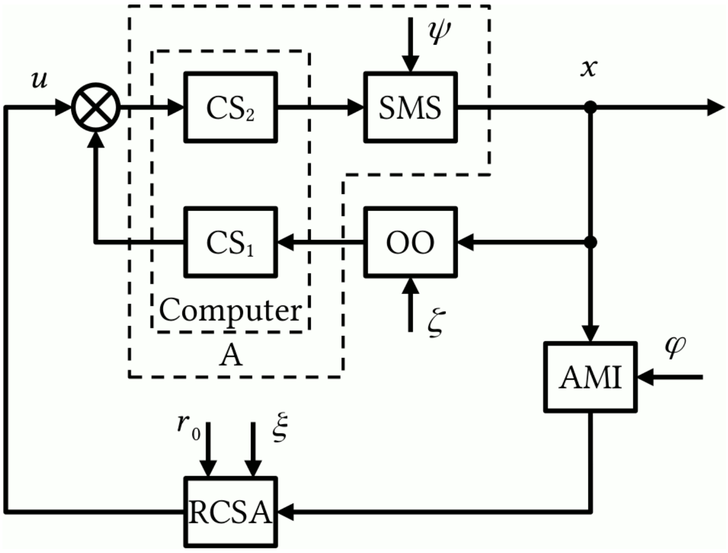

Figure 5: Structural diagram of the spatial movements stand for dynamic attestation of on-board meters.

The necessity of optimal observation of the state of on-board meters and the dynamic bench takes place in all the modes of real or simulated movements. Modern optimal observers are often built based on Kalman optimal filtering. At the same time, it is assumed that the measuring noise is uncorrelated with the signals of the object's state vector. In practice, this condition is often not fulfilled. To estimate the steady state of the object, it is possible to apply the spectral method of optimal estimation, which is convenient for practical implementation [7].

The block diagram of the formulation of the problem of optimal evaluation is shown in Figure 6.

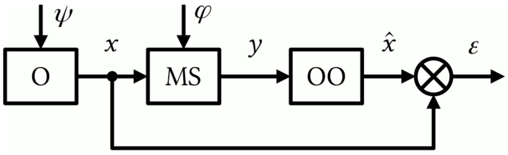

Figure 6: Block diagram of the optimal estimation.

In Figure 6, O is the estimation object, MS is the measuring system, OO is the optimal observer, x is the output signal of the estimated object, y is the measured signal, $\hat{x}$ is the estimate of the object’s output signal of the optimal observer, ε is the estimation error.

The unit of angular velocity sensors under study consists of three sensors. The measuring axes of these sensors are arranged in three directions, which are perpendicular to each other. To carry out the dynamic certification, the tested measuring instrument is located at the centre of the stand's platform in the following way. The axes of sensitivity of the sensors are directed along the axes of the cardan suspension, along which the platform is rotated by heading, pitch, and roll. The vector of input signals vector for the angular rate measuring instrument is calculated in the control system of the tested bench. We believe that an instrument for measuring angular velocity is mounted at some point. This point and the origin of the reference frame related to the platform's angular motion are coincided. Then the angular velocity vector can be given in the form:

$$\omega_{\mathrm{p}} = \begin{bmatrix} \omega_{\mathrm{p}x} \\ \omega_{\mathrm{p}y} \\ \omega_{\mathrm{p}z} \end{bmatrix} = \begin{bmatrix} \dot{\gamma} + \dot{\psi}\sin\vartheta \\ \dot{\psi}\cos\vartheta\cos\gamma + \dot{\vartheta}\sin\gamma \\ \dot{\vartheta}\cos\gamma - \dot{\psi}\cos\vartheta\sin\gamma \end{bmatrix}, \tag{1}$$

where ψ, ϑ, γ are small successive angles of platform rotation.

Since the angles of rotation of the platform are assumed to be small, expression (1) can be presented in the form:

$$\omega_{\mathrm{p}} \approx [\dot{\gamma} \quad \dot{\psi} \quad \dot{\vartheta}]'. \tag{2}$$

Expression (2) is a vector of the estimated angular velocity of the platform, that is, a vector of input signals of the angular velocity sensor block.

The imitation of linear accelerations of the stand's rotating platform at the point of attachment of the block of linear acceleration sensors is carried out by a displacement of the tested measuring instrument about the place of platform suspension. Then, both linear and angular motions influence the instrument for measuring acceleration at the same time. To determine linear accelerations directly, we can use calculating methods. Angle velocities of the platform and coordinates of the point of some displacement of the instrument for measuring linear accelerations about a point of the platform's suspension can be used as initial data for these calculations. It is known [29] that the absolute acceleration of the attachment point of the instrument for measuring linear acceleration is defined by the equation

$$\frac{dv}{dt} = \frac{d\omega}{dt} \times \rho + \omega \times \frac{d\rho}{dt} = u \times \rho + \omega \times \omega \times \rho, \tag{3}$$

where v is the vector of the absolute linear speed of movement of the attachment point of the instrument for measurement of linear accelerations; ω is the platform angular velocity vector; $\rho(x, y, z)$ is the radius-vector of the attachment point of the linear acceleration of the measuring instrument about the platform gimbals point with the appropriate coordinates x, y, z; u is the vector of the platform's angular accelerations.

Expanding the vector products of expression (3) and taking into account the previously introduced notations, we obtain:

$$w_{\mathrm{P}} = \begin{bmatrix} -(\dot{\psi}^2 + \dot{\vartheta}^2)x - (\ddot{\vartheta} + \dot{\gamma}\dot{\psi})y + (\ddot{\psi} + \dot{\gamma}\dot{\vartheta})z \\ (\ddot{\vartheta} + \dot{\gamma}\dot{\psi})x - (\dot{\vartheta}^2 + \dot{\gamma}^2)y - (\ddot{\gamma} + \dot{\psi}\dot{\vartheta})z \\ -(\ddot{\psi} + \dot{\gamma}\dot{\vartheta})x + (\ddot{\gamma} + \dot{\psi}\dot{\vartheta})y - (\dot{\gamma}^2 + \dot{\psi}^2)z \end{bmatrix}. \tag{4}$$

Expression (4) is a vector of calculated accelerations of the attachment point of the linear acceleration sensor block without taking into account gravitational components. Compensation for the component accelerations of gravitational forces can be carried out by hardware or computational means.

Identification of dynamic models of blocks of sensitive elements and their noise is carried out based on the spectral algorithm of structural identification. It represents the definition of dynamic models of blocks of sensitive elements and their measuring noise based on input and output signals measured during the experiment.

The unit of angular velocity sensors and the unit of linear acceleration sensors under study are mounted directly on the dynamic stand platform. The platform installed in the cardan suspension makes angular movements relative to three mutually perpendicular directions. The movements of the platform are ensured by three reversible motors installed behind each of the axes. The output signal of the platform is a vector of rotation angles $\theta = [\psi \quad \vartheta \quad \gamma]'$.

Angle motions of the platform are transformed into electrical signals and enter the control system of the stand. Software stand control signals are formed by noise generators and shaping filters, which are implemented by software. The communication unit converts digital signals coming from the computer to analog ones. Stand control signals are sent to the reversing motors through power amplifiers. A generator of standard signals is used to ensure the possibility of checking the stand.

During tests, the angular motions of the platform are registered, while the appropriate signals are taken from the feedback sensors. Hence, angular rates could be calculated by developing software that realizes the differentiation algorithm with high accuracy.

Based on the obtained data on input and output signals and the above-described algorithm, the dynamics models are determined. They represent the matrices of the transfer functions of the investigated blocks of sensitive elements of the strap-down inertial system, as well as the matrices of the spectral densities of noise at the output of the blocks under conditions close to operational ones.

6. Conclusions

The scientific and technical problems of modernization of full-scale and semi-full-scale simulation complexes were presented and briefly discussed, as well as the basic ways of successfully solving the mentioned problems were considered. The necessary science-intensive technologies for the proposed modernization can be obtained from the cited literary sources.

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