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Optimizing the selection of test-bench equipment for aircraft balancing

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This article analyses various aspects related to optimizing the selection of control and measuring test benches designed to determine the mass-centring and inertial characteristics of aircraft, as well as their balancing, at the final assembly stage. This article considers specific features of designing test benches capable of implementing the methods of unifilar and astatic pendulums, which determine the coordinates of the centre of mass and moments of inertia under a single installation of the apparatus under study in the measuring device, as well as the method of dynamic balancing, which provides precise determination of the mass-inertia asymmetry parameters of aircraft. The accuracy characteristics of the test benches under consideration are given.

Keywords: centre of mass, moment of inertia, axis of inertia, mass-inertia asymmetry, test bench, measurement method, measurement errors, experiment duration

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Development and operation of state-of-the-art unmanned aerial vehicles (AV) require detailed knowledge of their mass-centring and inertia characteristics (MCIC) – mass, positions of the centre of mass, moments of inertia. Considering low accuracy of theoretical calculations (10–20 %), which, as a rule, are carried out at the design stage, as well as unavoidable errors of the values of mass and spatial position of payload, sensors, and computer hardware arranged inside the AV housing, the most reliable method of obtaining MCIC data, characterizing static and couple unbalance, is either their experimental or combined experimental and computational determination with the use of test-bench equipment at the terminal stage of final assembly of the vehicle. Requirements to alignment of principal axes of inertia with geometrical axes are imposed on vehicles stabilized by spinning about the housing symmetry axis. Balancing aimed at elimination of the lateral offset of the centre of mass from the geometrical axis, as well as of skewness of the longitudinal principal central axis of inertia (PCAI) relative to the geometrical axis, unavoidable in the course of AV assembly and manufacture, is achieved through correcting the vehicle mass by attaching balance weights to the correction plane. Tolerances are established for the specified mass-inertia asymmetry parameters; the tolerance values are determined during the AV design.

The AV mass is often determined using a standard method of weighting on scales with an accuracy of up to 0.01–0.03 % of the vehicle mass. The remaining MCIC and requirements thereto are rather specific, with no equivalents in other sectors of industry, and their determination is ensured by special-purpose control and measuring test benches (as a rule, from 2 to 3 benches per vehicle or group of vehicles are used). In order to determine the coordinates of the centre of mass, as a rule, benches implementing the weight methods are used, and in order to determine the moments of inertia – benches operating on the principle of the inverted unifilar or physical pendulum [1–3]. Benches of both types are usually characterized by high labour intensity and low performance, besides, they require considerable labour and financial resources for periodical checks and maintenance. In addition, low instrumental precision of both bench types requires multiple measurement of desired parameters (with subsequent averaging of measurement results) in the course of balancing, which additionally extends the balancing experiment duration and reduces the measurement accuracy. Also, in the course of static balancing, the effect from installing a correction mass in the correction plane not passing through the article's centre of mass may lead to an increase of its couple unbalance; this is a matter of concern for the balancing specialists who therefore often have to adopt half-way solutions, thus adding the number of balancing steps, which, in turn, leads to a many-fold increase in the scope of measurements. As a result, sequential bench-balancing of only one vehicle can often last up to 10 working shifts or more. At that, the need to keep consistent environment throughout the entire balancing experiment is a considerably complicated engineering challenge. Multiple forced re-installation of the tested item from one bench to another contributes to additional measurement-method errors. The specified circumstances invoke the development of test-bench equipment that would enable reduction of time of MCIC determination and AV balancing and the increase of accuracy of the same.

The use of multi-purpose control and measuring test benches, ensuring determination of the full range of MCIC at a single installation of the tested vehicle in the measuring device, allows to avoid measurement-method errors associated with multiple vehicle re-installation on different benches in the course of measurement, and reduce the balancing experiment duration [2]. For the cases of necessary significant increase of the accuracy of determination of certain MCIC, for example of mass-inertia asymmetry parameters with their nominal values close to zero, and, consequently, increase of the balancing accuracy, there has been an emerging trend of using the dynamic balancing test benches. The balancing test benches allow to measure mass-inertia asymmetry parameters immediately relative to the AV geometrical axis if this axis is aligned with the rotation axis, available on the balancing test bench, to a high precision. Besides, high performance of the balancing test benches (as a rule, single run-up time doesn't exceed several minutes, and the entire measurement cycle – one and a half to two hours) and the possibility to determine and correct both tested mass-inertia asymmetry parameters simultaneously, reducing the balancing time, makes them an advantageous tool for high-precision AV balancing.

As an example of a multi-purpose test bench, let us consider the test bench designed and manufactured for determination of the full range of MCIC of a conical AV, with a single installation of the tested vehicle on the test desk, and implementing a method of inverted unifilar suspension [4]. The test bench diagram is shown in Figure 1.

Test desk 1 is arranged horizontally and supported by gasostatic bearings 2, and rigidly connected to one end of torsion bar 3, another end of which is fixed to the centre of diaphragm 4 installed in the bottom of test bench case 5. The tested AV (not shown in Figure 1) is installed and secured inside positioning element 7 fixed to carriage 6 capable of fixed displacement

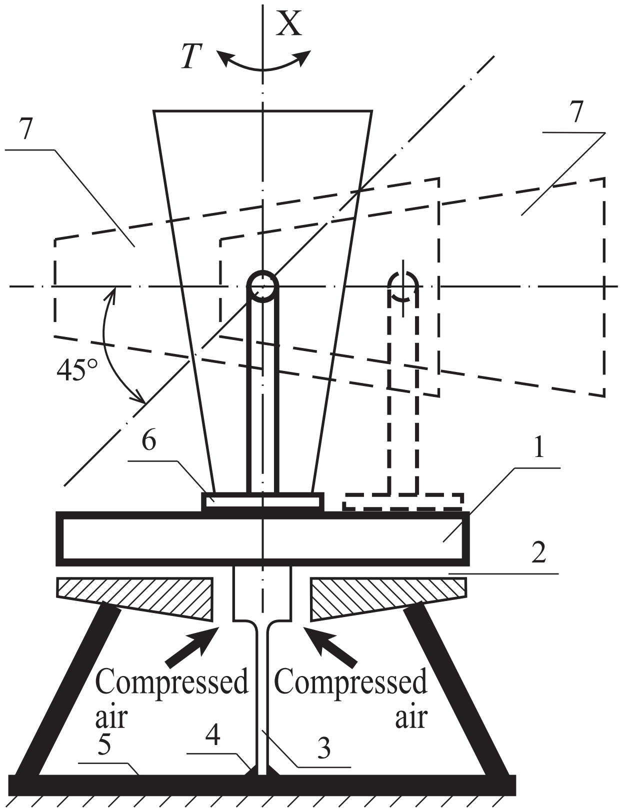

Fig. 1. Diagram of unifilar test bench with a possibility to horizontally displace the tested item:
1 – desk; 2 – gas bearings; 3 – torsion bar;
4 – diaphragm; 5 – housing; 6 – carriage;
7 – positioning element

in the horizontal plane. The positioning element ensures setting of the tested item to the preset attitude positions. The carriage located on the test desk can travel to the preset fixed positions on the test desk. Compressed air fed to the gasostatic bearings from the shop LP pneumatic circuit (up to 0.6 MPa) is used as a medium.

The desired values of AV MCIC are determined based on the results of measuring periods *T* of small torsional oscillations made by the vehicle installed on the test desk about the vertical axis, formed by an elastic torsion bar, in six attitude positions: with the AV geometrical axis in vertical and horizontal positions, as well as at an angle of 45 degrees to the horizon. The measurements are also made with the geometrical axis located horizontally, but with the vehicle shifted in the horizontal direction to a specified distance relative to the torsional oscillation axis. The values of lateral offset of the centre of mass and deflection angle of the longitudinal PCAI relative to the geometrical axis of the vehicle are calculated using special methods and measured values of mass, coordinates of the centre of mass, and moments of inertia.

However, in practice, low instrumental precision of the unifilar test bench, unsteady elements (such as carriage, positioning element), being part of engineering facilities, require multiple measurements with subsequent averaging of the results to increase the accuracy of MCIC determination. This significantly limits the advantages of the method, which are achieved through the higher bench performance, compared with the sequential MCIC measurement method implemented on a separate centring test bench and a test bench for determining the moments of inertia. For example, the accuracy achieved in determining the lateral coordinates of the centre of mass and skewness of the longitudinal PCAI relative to the AV geometrical axis was 0.05 mm and 3 angular minutes, respectively [4]. This is comparable with the results of determining the same mass-inertia asymmetry parameters with the sequential use of a separate centring test bench and a test bench for determining the moments of inertia. Nevertheless, the use of the test bench allowed to reduce the balancing experiment duration down to 3-4 working shifts though avoiding AV re-installation. At the same time, the need to set the tested item to a vertical position in the course of measurement imposes limitations on the height of ceilings in the production premises, where the balancing is carried out, and the positioning element, ensuring installation and fastening of the vehicle in the test bench measuring device and setting of the same to the required attitude positions, limits possible changes in the size and shape of the AV housing.

To determine the coordinates of the centre of mass and moments of inertia of the AV, including the long-length ones, and including those having a profiled housing, a control and measuring test bench that implements the astatic pendulum method was designed and manufactured [5–7]. The test bench ensures determination of the full range of MCIC at a single installation of the tested item on the test desk.

The mechanical installation of the test bench, as shown in Figure 2, is performed by means of tilting platform 1 with positioning element 5 and two cradles 6 and 7 for fixing tested item 8 installed on the same. The platform oscillates in vertical plane, which is ensured by means of lever 3 and an elastic element – spring 4.

The desired values of AV MCIC (except for the longitudinal coordinates of the centre of mass) are determined based on the results of measuring periods T of small pendular oscillations made by the vehicle installed on the test desk about the horizontal axis under the action of the elastic spring. Measurements are performed when the AV geometrical axis is located at an angle of 0°, 45°, and 90° relative to the axis of oscillation. The vehicle attitude position is changed using the positioning element. The longitudinal coordinates of the centre of mass are determined based on the principle of static balancing, which is performed by means of attaching test weights of a known mass to the platform at a known distance from the axis of oscillation [7]. The values of lateral offset of the centre of mass and deflection angle of the longitudinal PCAI relative to the geometrical axis of the vehicle are calculated using special methods and measured MCIC.

Availability of a set of interchangeable cradles for the test bench allows to install and test AV MCIC having both cylindrical and conical housings. The test bench ensures determination of the coordinates of the AV centre of mass and moments of inertia and allows to complete this work with the vehicle set only in the horizontal position, which removes the limitations imposed on the height of ceilings in the production premises, where the work is carried out. The errors obtained during the measurements did not exceed 0.1 mm, when determining the lateral coordinates of the centre of mass, and 12 angular minutes [7]. At the same time, the AV balancing duration was

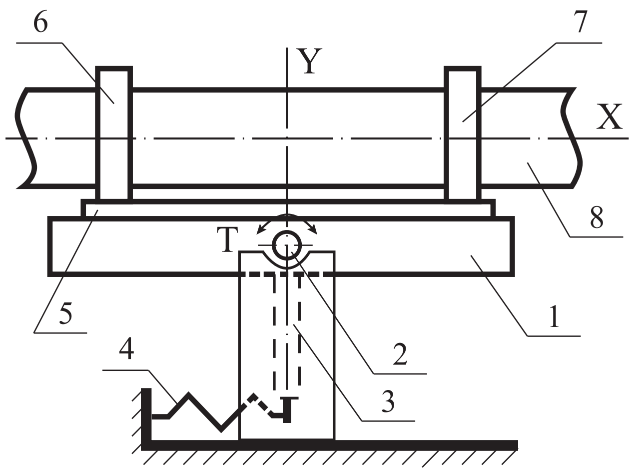

Fig. 2. Diagram of test bench mechanical installation: 1 – platform; 2 – hinge; 3 – lever; 4 – spring; 5 – positioning element; 6 and 7 – cradles; 8 – tested item

reduced down to 1.5–2 working shifts. The simplicity of mechanical installation design facilitates its scaling and respective (if necessary, significant) increase of load-carrying capacity.

As an example of a test bench referring to the second optimization type, let us consider the dynamic balancing test bench with a vertical rotation axis and rigid supports implemented in the form of conical gasostatic bearings, designed and manufactured for high-precision determination of the mass-inertia asymmetry parameters and balancing of conical AV [8, 9]. The test bench diagram is shown in Figure 3.

The test bench consists of two – lower 2 and upper 7 – oscillating suspensions having identical design; each suspension is designed as a pair of elastic plane-parallel plates, which hold lower 17 and upper 14 gasostatic bearings, respectively, that are cantilever fitted on vertical stand 6 installed on powerful base 1. The upper bearing is combined with pneumatic acceleration mechanism 15 (pneumatic rotary actuator) and the lower one is combined with pneumatic braking mechanism 3 (pneumatic brake).

The test bench is equipped with truncated-cone-shaped service adapter 5 designed as a rigid casing, the external side surface of which corresponds to the working surfaces of gasostatic

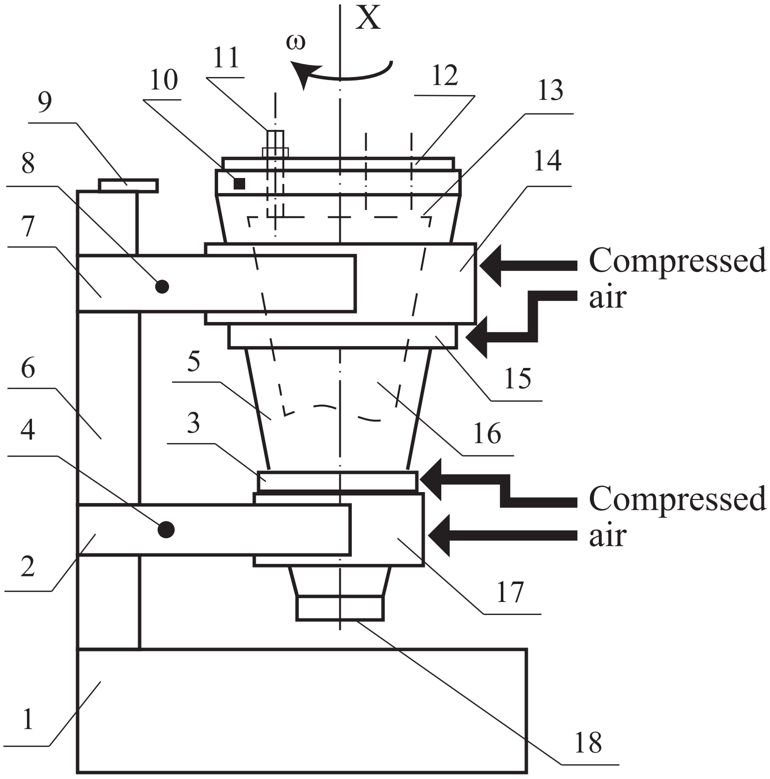

Fig. 3. Diagram of balancing test bench: 1 – base; 2 – lower oscillating suspension; 3 – pneumatic rotor braking mechanism; 4 – force sensor "low"; 5 – service adapter; 6 – vertical stand; 7 – upper oscillating suspension; 8 – force sensor "up"; 9 – unbalance phase reference sensor; 10 – mirror reflector; 11 – retaining stud; 12 – profile cover; 13 – upper correction plane; 14 – upper gasostatic bearing; 15 – pneumatic actuator; 16 – tested AV; 17 – lower gasostatic bearing; 18 – lower correction plane

bearings. The adapter inner support surfaces correspond to the basic mounting faces of tested AV 16, which is installed on these supports with its front part down, thereby forming the so-called composite rotor. The vehicle is fixed inside the adapter using special profile cover 12 and three retaining studs 11, evenly distributed on the cover around circumference. This excludes the possibility of vehicle 16 displacement relative to adapter 5 in the course of acceleration and braking of composite rotor. The use of the adapter also excludes the possibility of mechanical contact of the tested AV with the balancing equipment in the course of measurements and ensures materialization of the second (lower) correction plane 18 used for adjustment of the test bench measuring system. At that, the standard correction plane of the vehicle, which, as a rule, is structurally arranged near its end face, is used as the first (upper) correction plane.

Compressed air is used as a medium, which is fed to the gasostatic bearings and pneumatic acceleration and braking mechanisms from the shop LP pneumatic circuit. The tested vehicle is balanced on the test bench as a separate part of the composite rotor. In the course of experiment, the desired mass-inertia asymmetry parameters are calculated based on the results of determining the values and angles of unbalances that are in force in the upper and lower correction planes. The specified parameters of unbalances are determined based on the results of measuring the amplitudes and phases of vibrations of gas supports, which is performed using dynamo-measuring sensors 4 and 8 installed in elastic elements of upper 7 and lower 2 oscillating suspensions, respectively, and fibre-optic phase reference sensor 9 with mirror reflector 10 fixed on the adapter side surface. The phase reference sensor is also used to monitor the speed of composite rotor ω [10].

Before balancing with the use of other equipment and other measuring instruments, the AV mass, longitudinal position of its centre of mass relative to the standard correction plane, as well as moments of inertia shall be determined. If a value of at least one mass-inertia asymmetry parameter exceeds the corresponding maximum allowable value, the balancing analysis shall be carried out to reach the established standards, for example, with optimization based on the criterion of reaching the minimum value of any tested mass-inertia asymmetry parameter [11, 12], and the AV mass shall be corrected by attaching balance weights to upper 13 (standard) AV correction plane. If the calculation has demonstrated impossibility of bringing both mass-inertia asymmetry parameters to the values not exceeding the maximum allowable values, then the tested vehicle is rejected and forwarded to the manufacturer for rearrangement, thus avoiding knowingly pointless balancing operations, which ensures significant reduction of the balancing experiment duration.

The errors obtained during the measurements of lateral offset of the centre of mass and deflection angle of the longitudinal PCAI using the considered balancing test bench did not exceed 0.01 mm and 1 angular minute, respectively. And the entire AV balancing process, for example, when using an unifilar test bench to determine the longitudinal coordinates and moments of inertia of the vehicle, as a rule, does not exceed 1 working shift.

All considered test benches are computer-based and represent modern automated control systems, which include both control and measuring test bench with the necessary technological equipment and software and hardware complex that ensures equipment control, mathematical calculations, and generation of reporting documents [13–15]. Besides, the system necessarily includes a working standard (set of standards) intended for testing the standardized technical characteristics of a test bench, which is performed at certain intervals during the entire service life of a test bench [16, 17]. As a rule, mass-centring characteristics and basic mounting faces of a working standard correspond to the specified characteristics and surfaces of the balanced AV.

Thus, we may note that in the field of development and improvement of methods and means of MCIC control and AV balancing, two options, allowing the testing engineers to select optimum versions of bench equipment, have recently emerged. One option includes the development of multi-purpose control and measuring test benches, ensuring determination of the full range of AV MCIC at a single installation of the tested vehicle in the measuring device, which makes it possible to reduce the range of used test benches to one test bench, exclude the necessity of multiple vehicle re-installation during measurements, and to reduce the measurement duration at an acceptable measurement accuracy. When designing a test bench and technological equipment, the main goal is to minimize the “vulnerability” of the same to changes in mass, dimensions, and shape of AV housing, as well as the requirements for production premises. However, the quest for greater universalisation during the test bench design often leads to a degradation of accuracy of tested MCIC measurements. As another option, we can consider the development of dynamic balancing test benches, which provide significant increase of the accuracy of mass-inertia asymmetry parameters determination and, consequently, an increase of the accuracy of AV balancing, as well as a reduction of the balancing experiment duration. At that, it is worth mentioning that the need for preliminary determination of the longitudinal coordinates and moments of inertia of AV requires the use of additional test and measuring equipment together with the balancing test bench. The resulting redundant information on MCIC allows to avoid gross inaccuracies during the calculation of correction weights by means of comparing the results of MCIC testing in different systems.

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К вопросу оптимизации выбора стендового оборудования, используемого для уравновешивания летательных аппаратов

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Проанализированы аспекты, касающиеся оптимизации выбора контрольно-измерительных стендов, предназначенных для определения массо-центровочных и инерционных характеристик и балансировки летательных аппаратов на заключительном этапе их общей сборки. Рассмотрены особенности конструкции стендов, реализующих методы унифилярного и астатического маятников, обеспечивающие определение координат центра масс и моментов инерции при однократной установке аппарата на измерительное устройство, и метод динамической балансировки, обеспечивающий прецизионное определение параметров массо-инерционной асимметрии аппаратов. Приведены характеристики точности стендов.

Ключевые слова: центр масс, момент инерции, ось инерции, массо-инерционная асимметрия, контрольно-измерительный стенд, метод измерений, погрешности измерений, продолжительность эксперимента

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Область научных интересов: системы контроля и испытаний вооружений и военной техники.