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Designing the Set of Flight Experiments for Exploration of Critical Flight Conditions in Case Failure and Damage of Lifting and Control Aircraft Components with a Point of View of Systems Approach

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The features of design of flight tests for research of critical flight modes in case of failure and damage of lifting and control aircraft units with the help of free-flying dynamically similar models are analyzed; recommendations to reduce the time and costs of such tests are developed. The performed analysis clearly demonstrated the methodological advantages of conducting experiments in the free flight of the unmanned model. The absence of the risk of crew loss and the ability to perform a relatively more strong model at the design stage allows us to determine the subcritical and overcritical values of the investigated parameters in the first test launches. In general, the convergence of the process of searching for critical values of the parameter with the required accuracy is significantly increased.
Keywords: system analysis, critical modes of flight, aircraft structural damage, flight research

Introduction. Formulation of the problem. Relevance

When developing the new aerospace vehicles of both civil and military purpose, the highest level of reliability and flight safety have to be foreseen. At the same time, it is necessary to minimize, as much as possible, the term of aircraft design and test to prevent from premature obsolescence and loss of competitive ability. Experimental studies of critical flight conditions (e.g., spin, flutter, flights in case damaged onboard load-carrying and control components, etc) and development of Aircraft Flight Manual under emergency conditions cause the heavy material and time resources to be in need and a loss of high-cost preproduction model and test-pilots to be probable. The task of pecuniary and time optimization of flight test, the decrease of risk of flight experiments is an **urgent** problem that may be solved thoroughly on the base of systems approach to a problem of optimization of programs and schedule[1] of flight tests.

1. Interrelation with scientific works. The level reached

Design of flight test of full-scale aircraft is an independent science with own terminology and methodical literature [e.g. 1]. Wide experience of mentioned tests and their risks have accumulated by the Flight Research Institute and summarized in the anniversary anthology [2]. However, full-scale tests of critical modes of aircraft flight un-

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[1] Unfortunately, there is an inconsistency as to flight-test special terms in the available sources of information. The following terms are used here**: test flight program** (программа испытательного полета) is a sequence of aircraft flight modes that are realized during the test flight due to activity of crew or automatic control system; **schedule of test flights**, test schedule (план испытательных полетов) is a set of information for determining the number, terms and programs of the test flights (taking into account the results of preceding flights); the **theory of design of experiment techniques** (теория планирования экспериментов) is the theory of the development of a set of measures for an effective experiment organization. The main purpose of the **experimental design techniques** is to obtain the maximum accuracy on condition of minimum tests.

der conditions of combat and operational damages were not carried out because their high-level danger (by reason of highly probable loss of the aircraft). Some modes (stalling, spin, super-maneuverability… of undamaged airplanes with different types of stores) were studied by specialists of the Inter-branch Institute of Aircraft Flight Modes Physical Modelling Problems (NII PFM KhAI) of the National Aerospace University “KHAI” with the help of large-scaled free-flying dynamically-similar models (FDSM) [2].

When anticipatory researching of flight dynamics and aeroelastic phenomena of an aircraft with damaged lifting surfaces and control system failure, the high efficiency of usage of FDSM [1] become apparent the most clearly [3; 4]. However, their implementation requires a preliminary methodological study, one aspect of which is set out in this paper.

2. The purpose

The **purpose** of this analysis is to reduce the time and cost of research of dangerous phenomena of flight dynamics and aeroelasticity in case of damage of lifting and control aircraft surfaces by means of the FDSM through the development of rational design of tests schedule the number of required test flights to be reduced.

This analysis is based upon the following theoretical grounds:

- system analysis that allows to make a rational and reasoned decision in case there are no complete information about studied object (phenomenon) (such as the value of the critical parameters or effective crew operation during studied in-flight conditions);
- mathematical statistics, in particular the theory of experiment design that studies the principles of optimal design of experiments;
- technique of analysis, processing and interpretation of experimental data in the presence of random errors.

3. Main results of the work

The classical statement of the problem of design of experiments is as follows. There is a certain experimentally investigated (measured with random errors) function of the parameters that characterizes the criticality of the phenomena under investigation $f(x_1, x_2, x_3 \dots x_n, z_1, z_2, z_3 \dots z_m)$. This function depends on n parameters of the flight mode $x_1, x_2, x_3 \dots x_n$ that are known to the experimenter, may be varied by him during an experiment within the admissible values $X_1, X_2, X_3 \dots X_N$). This function depends also on m parameters $z_1, z_2, z_3 \dots z_m$; the effect of these parameters upon the investigated function is unknown to the experimenter, they can not be varied because of a decrease of the cost or the risk of experiments. At that, the purpose of the test flights is to state the effect of some (might be — all) parameters z_i (or their functions) or to test existing hypotheses about mentioned effect. During experimental tests, some of these weakly-studied factors (parameters) take on random, uncontrolled and unrecorded values that result in random errors. (To put it more precisely, there are no "random" changes in the studied parameter; any change has its own grounds. However, not all of these grounds are known to the experimenter, not all of these changes may be moni-

[1] Pay attention: FDSM is a highly effective tool used when aircraft developing. They are not intended for sale or export. Therefore, in the available sources of information the usage of FDSM is usually only referred to increase the prestige of firm-designer and aircraft. Information about the models arrangement, their testing programs and even similarity criterion, as a rule, are not cited.

tored. Arbitrary, spontaneous, uncontrolled change of the parameters, the cause of mentioned change (unknown or neglected) is a source of so called "random" error)[1].

According to the purpose of experiments, the **criterion** of optimality of layout of the design of experiments[2] is developed. The **layout of the experiment** is a set of the associated values of parameters $x_1, x_2, x_3 \ldots x_n$ and methodically adjacent variables of the Z set; mentioned values are prescribed during experiment.

It should be noted, the optimum layout of the experiments can be worked out before the execution phase of analysis of aircraft survivability only in special, infrequent situations[3]. Usually the initial layout of the experiments is revised on-the-fly, during experiment execution and accumulation of information about the nature of parameter effect upon the studied phenomenon (described with the function f $f(x_1, x_2, x_3 \ldots x_n, z_1, z_2, z_3 \ldots z_m)$.

Mentioned approach to a problem is (theoretically) the basic advantage of experiments with the help of the FDSM as against the full-scale flight test of aircraft. **For the FDSM, the set X_1 of permissible values of experiment parameters is wider** if not quantitatively (over a range of parameter change), then qualitatively (over the set of variable parameters of the experiment, i.e. the potency n of the set X).

This is a basic difficulty of the FDSM-research: when testing a full-scale aircraft, the unknown influencing parameters $z_1, z_2, z_3 \ldots z_m$ may be rendered in more reliable way as against FDSM-testing. Some parameters of this set can not be rendered in the experiment with the help of the model because of their uncertainty, and some — because it is impossible to scale model to represent adequately the influence of mentioned parameters under the stipulation of engineering feasibility of the model [5; 6]. For example, an attempt to represent adequately the action of inertial forces (Newton's criterion), gravitation forces (Froude's criterion) and the forces of viscosity of ambient flow and related processes (Reynolds' criterion) leads to the trivial solution — all scales of similarity are equal to the unity; in this case the full-scale flight test of an actual aircraft is in need in spite of imperfection of such test[4].

Usually the flight test with the FDSM results in the reducing the required amount of test flights. As to full-scale experiment under supercritical values of studied parameters, there is a theoretical or methodological impossibility of their carrying out or their execution is in need of special measures that cause the schedule time and cost of

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1 For example, as it is shown by an experience, the spread of spin parameter of production airplanes may be 30%.

2 Usually the effect of parameters zi is judged by least-squares method; the hypotheses of the effect of parameters zi are judged by the analysis-of-variance method (for example, by Fisher's F-number). With implementing both methodological ways, any function of variance and correlation coefficients obtained with the help of least-squares procedure may be used as optimality criterion of test program with a predetermined (e.g., according to financial expenditure) amount of experiments. There is another methodical way of experiment design: to develop a program that ensures the desired accuracy of the results (or desired probability of a reliability of hypothesis to be tested) under minimum amount of experiments.

3 E.g., in the presence of linear or, at least, monotonic dependence $f(x_1, x_2, x_3 \ldots x_n, z_1, z_2, z_3 \ldots z_m)$ on z_i.

4 Sometimes a so-called "model-full-scale" airplane is tested, that is a modified full-scale airplane, such as unmanned version of manned aircraft or unmanned aerial vehicle (UAV) that is re-equipped by replacing the portion of payload and onboard equipment with the system of emergency get-out the critical conditions.

works to be increased greatly and the accuracy and reliability of obtained data to be decreased too. So when using the full-scale experiments for setting of flight limitations of new aircraft, fair quantity of test vehicles is in need. For example, a stall and spin of an aircraft are very dangerous phenomena. But most of the aircraft (virtually all production aircraft) can be pull out the spin in case necessary altitude margin; if there is no necessary altitude margin, the modern life-saving equipment is used to save the life of the crew of experimental aircraft. So, the obtaining, at least, two experimental points (subcritical and supercritical) results in the determination of searching range of the criticall value of the parameter and the effective design of flight experiments to narrow the mentioned range thanks to obtaining new experimental points that localize the critical value with the required accuracy (Fig. 1).

When studying the flutter limitations, there is quite another matter. Flutter of modern aircraft is very intense, "explosive" phenomenon that results both in structural damage and loss of crew. Therefore, the anti-flutter measures are tested at flights at the speeds that are little higher the maximum operating ones.

It is necessary to note: anti-flutter measures are high-cost, they result in increase of frame weight (sometimes — up to 15...18%) or demands the usage of anti-flutter additional weights (sometimes — up to tens of kilograms).

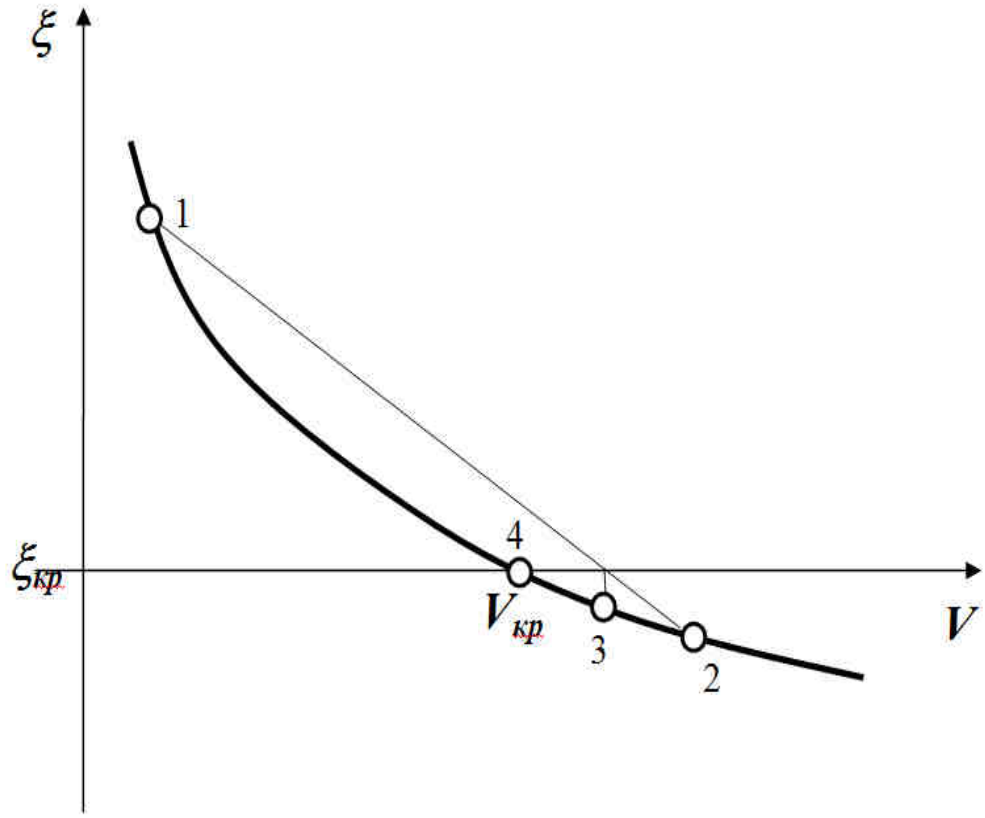

Fig. 1.
V — flight speed; ξ — parameter of mode criticality; $V_{кр}$ $\xi_{кр}$ — critical values of speed and parameter

In case there is no flutter phenomenon at these modes, the decision is taken about aircraft quantity production and putting into operation. But questions of effectiveness of taking measures, possibility of lessening the additional weights, accuracy of `mathematical models remain undecided. And what is more, in case of suspicion of in-flight flutter, the flight tests should be stopped immediately according to normative documents.

Only during unique tests (e.g., tests carried out by the Flight Test Institute under the leadership of M. Klyachko, Doctor of Science [2]), the careful and slow approach "from below" to the critical flutter rate (Fig. 2) was carried out as follows: step by step "parameter margin" was determined with maximum accuracy (by analyzing the decrement of damping of structure vibrations under harmonic or pulsed excitation of its fluctuations) under the risk to loss of the aircraft and its crew with the "ideologist" of such testing.

To study mentioned phenomena, the flight test with the help of unmanned physical models are especially effective due to significantly lower cost of model under test and possibility of anticipatory flight test: design, manufacturing and test of models are carried out in a short space of time when full-scale aircraft is not yet manufactured and is in the computer memory only; so corrective actions (discovered by means of model tests) does not result in high expenses and increase in schedule time of the design of the actual aircraft.

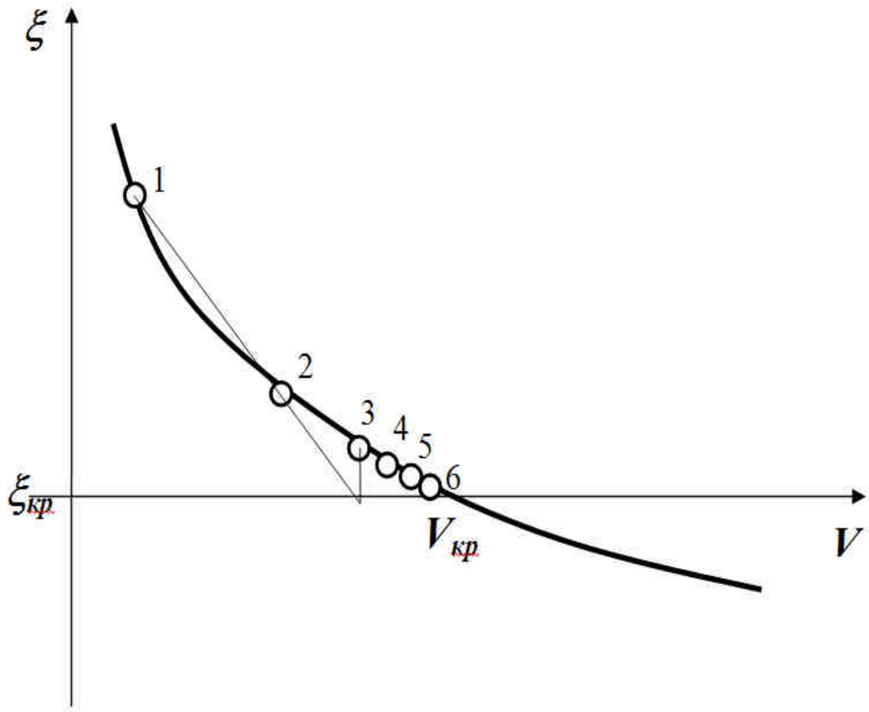

Fig. 2.

It is known that the interpolation gives more accurate results in comparison with the extrapolation. However, in the specific conditions of flight test, the error of approximation may result in the loss of aircraft and crew. As it is shown in Fig. 3, the extrapolation (that is used in case it is impossible to test supercritical modes) suggests the following step as recovering to supercritical, inadmissible modes that may result in crash. So, when designing the flight test, the experimenter has to know the functional relations parameter of dangerous phenomenon (e.g. the value of the critical angle of attack, breaking overload, the maximum number of cycles of loading), but a set of such parameters to define the multidimensional space of feasible initiation (or guaranteed absence) of this phenomenon (e.g., conditions of beginning the engine's surge; the speeds of spin stall of the aircraft for the range of its flight altitudes, centre of gravity position, aerodynamic layout, between the studied parameter of criticality of the mode and flight speed.

Unfortunately, when studying the critical modes of flight, the phenomena of aeroelasticity and problems survivability of aircraft and helicopters, it is often necessary to limit the program of experiments to a few unique tests because of the high cost (and sometimes danger) of each experiment. In this case it is necessary to abandon the methods of the optimal design of experiments and statistical data manipulation. In addition, usually mentioned research should result in obtaining not single value of studied values and type of damage; limitation of flight modes by flutter, divergence and buffet; conditions of existence of naked flame as function of the speed of airflow,air density (partial pressure of oxygen), air turbulence, temperature of air and fuel, etc).

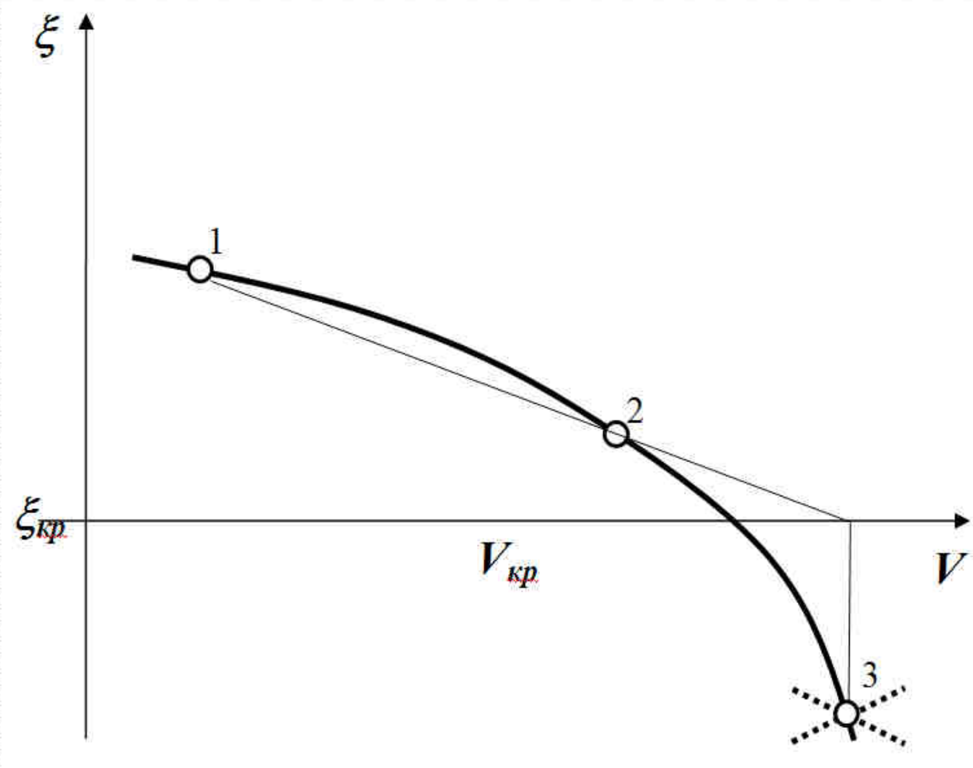

Fig. 3

Methodically, most of mentioned characteristics should be determined in a number of discrete points of aircraft flight modes; mentioned points should be selected in a way that there is no doubt about interpolation of the experimental data upon other modes. Mentioned supporting points-modes are selected on the base of physics of studied processes; form of region of possible occurrence of dangerous phenomena (pre-studied for airplane-analogue or for other layouts and centre of gravity position,of aircraft been tested); the experience of similar studies; the financial capacity and permissible run-time of the research program. It is natural to minimize the number of such tests under the assumption of sufficiency for valid interpolation. The process of design of such test is intuitive and difficult-to-algorithmization process.

There is another feature of considered research: the experimenter is interested not only the error magnitude of the determination of the critical value of the parameter, but also the sign of this error. Sometimes, such methods are used that have less precise but guaranteed "pessimistic" error (e.g., give too high critical stall speed, the minimum altitude of actuation of life-saving system, so on or give too low value of the critical flutter speed, the critical size of damage or the number of loading cycles of unit breaking).

When designing the flight test, the most dangerous and most characteristic layouts of aircraft (location of suspended loads, positions of wing high-lift devices, centre of gravity position of an airplane, fuel tanks filling, etc) and failures and damage of on-board systems are considered. For other modes only tests check are used.

Conclusions and prospects of research

1. The use of large-scaled free-flying dynamically-similar models (FDSM) is characterized by extraordinary methodical capabilities that may be realized on the base of systems analysis to the complex of concerning problems.

2. The application of methods of systems analysis to the designing of flight tests of studying the critical flight modes by means of the FDSM results in high efficiency, reducing the time and cost of experiments, possibility to check the repeatability of the data.

3. The future research will be directed to systems analysis of the methodological possibility of different ways to study the dangerous phenomena of flight dynamics and aeroelasticity in case failure and damage of lifting and control aircraft units and aircraft control system.

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Системний підхід до розробки програм експериментів з дослідження критичних режимів польоту при відмовах і пошкодженнях несучих і керуючих агрегатів

На основі системного аналізу досліджено особливості складання програм льотних досліджень критичних режимів польоту при відмовах і пошкодженнях конструкції літака за допомогою вільнолітаючих динамічно подібних моделей і розроблено рекомендації щодо скорочення термінів і витрат на їх проведення.

Виконаний аналіз наочно продемонстрував методичні переваги проведення експериментів у вільному польоті безпілотної моделі. Відсутність ризику втрати екіпажу і можливість на етапі проектування виконати модель відносно міцнішою дозволяє у перших же випробувальних пусках визначити докритичні та закритичні значення досліджуваних параметрів. В цілому збіжність процесу пошуку критичних значень параметра з необхідною точністю значно збільшується.

Ключові слова: системний аналіз, критичні режими польоту, пошкодження конструкції літака, льотні дослідження

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Keywords: system analysis, critical modes of flight, aircraft structural damage, flight research

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