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INFLUENCE OF ALTITUDE-VELOCITY LIMITATIONS OF PHYSICAL MODELLING PROBLEMS ON THE MAIN PARAMETERS OF FREE FLYING AIRCRAFT MODELS

Summary. Reducing the time and cost of aircraft creation can be achieved by improving the accuracy, informativity, and efficiency of flight research results on free flying dynamically similar models (FDSM). In particular, this is ensured by the development, improvement, generalization, and application of theoretical and methodological foundations for the creation of FDSM. This paper is structured from these positions. It does not reveal all the peculiarities of the design, manufacture, and testing of FDSM but shows the influence and dependence of altitude-velocity limitations of physical modelling problems on the main parameters of FDSM. At the same time, a literature review was performed to study and analyze the achievements and problems of physical modeling of aircraft flight on FDSM. The conditions and scales of similarity used in the design, manufacture, ground and flight tests of FDSM, and flight research are considered. The influence on the main parameters of FDSM of modelling problems, together with similarity conditions and the system of relations of parameters of FDSM, of the full-scale

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aircraft and environment; design conditions; technological limitations; flight-technical requirements; and operational limitations is emphasized. It is established that if mass is taken as the objective function in the design of an FDSM, then in order to achieve its minimum, one should strive to create an FDSM with the minimum possible linear sizes. To take into account the auto-model limitations of modelling problems, a special method for predicting flight characteristics and scientific-research capabilities of an FDSM has been developed and presented.

Keywords: altitude-velocity limitations, modelling problems, main parameters, free flying dynamically similar aircraft models

1. INTRODUCTION

The most effective solution to many problems of creating modern aircraft is the application of a method that uses as a flight research tool a free flying dynamically similar aircraft model (FDSM), which is an unmanned aerial vehicle for research purposes, reusable, capable of remotely-piloted or automatic flight according to a given program [1].

As an example, Figure 1 shows images of a full-scale aircraft and its FDSM in AirStar NACA program [2].

Fig. 1. Full-scale aircraft and its FDSM in AirStar NACA program

The process of creating an FDSM has a whole set of features that distinguish it from a similar process for aircraft of other purposes. The main one is the is necessity to satisfy the accepted (taking into account the modelling tasks) similarity conditions at all stages of design, manufacture, ground and flight tests of FDSM, as well as to conduct both leading and accompanying flight research. To reveal the features of creating FDSM it is necessary to answer numerous questions, which cannot be done in one small work. However, it is feasible to show the influence and dependence of altitude-velocity limitations of physical modelling problems on the main parameters of FDSM.

The purpose of this work is to reduce the time and costs of aircraft creation by increasing the accuracy, informativity, and efficiency of flight research results on FDSM, which is provided by the development, improvement, and application of theoretical and methodological bases of their creation.

2. LITERATURE REVIEW ON PHYSICAL MODELLING OF AIRCRAFT FLIGHT, THEORETICAL AND METHODOLOGICAL BASES FOR CREATING FDSM AND CONDUCTING FLIGHT RESEARCH ON THEM

Since 1927, NACA carried out a set of works to create FDSM of various aircraft and conduct flight research of flight dynamics on them. At the same time, a number of countries have developed theoretical and methodological apparatus for the design, manufacture, and flight testing of FDSM, as well as flight research on them. These principles, methods and techniques are based on extensive experimental material and have been repeatedly tested in the process of real design and flight research. Currently, not all problems in physical modeling on FDSM have been solved: conclusions and recommendations for known problems require analysis, improvement, and generalization, and new problems require different approaches to their solution [2, 4, 6].

3. SCALES OF SIMILARITY OF THE MAIN PARAMETERS OF FDSM

The similarity conditions in the creation of FDSM eliminate a number of design and manufacturing problems common to aircraft for other purposes. These conditions together with the conditions of feasibility of FDSM and flight-technical requirements, impose on the parameters of FDSM and conditions of flight experiments a system of relations, the correct resolution of which is one of the most difficult theoretical problems of this type of physical modelling. Reliable transfer of the results of research flights of FDSM to a full-scale aircraft is possible only if the conditions of geometric, kinematic, and dynamic similarity are met: an FDSM should have the same external shape as a full-scale aircraft, the position of the center of mass (CM) required by similarity and mass-inertial parameters, elastic-geometric characteristics, and similar laws of the automatic control system. As a result, an FDSM will behave in flight in the same way as a full-scale aircraft under relevant conditions [1, 3, 5].

In the analysis of similarity issues, first of all, attention is paid to the scales of similarity, which allow us to find the relationship between the relevant parameters and characteristics of a full-scale aircraft and an FDSM, as well as the parameters and characteristics of the modeled phenomena. Since for an FDSM its characteristic linear size ℓ_m, mass m_m, axial I_{xm}, I_{ym}, I_{zm} and centrifugal I_{xym}, I_{xzm}, I_{yzm} moments of inertia are taken as the main parameters, the scales of similarity between the main parameters of a full-scale aircraft and an FDSM are as follows [5]:

$$k_\ell = \frac{\ell_n}{\ell_m};\;\; k_M = \frac{m_n}{m_m} = k_\rho k_\ell^3;\;\; k_I = \frac{I_{jn}}{I_{jm}} = k_\rho k_\ell^5 \; (j = x, y, z, xy, xz, yz), \tag{1}$$

where k_ℓ – scale of linear size; ℓ_n – similar to ℓ_m, (m) characteristic linear size of the full-scale aircraft, (m); k_M – mass scale; m_n – mass of the full-scale aircraft (kg); k_I – scales of moments of inertia; I_{jn} – moments of inertia (axial and centrifugal) of a full-scale aircraft with respect to axes similar to the coordinate system of an FDSM, $(\mathrm{kg} \cdot \mathrm{m}^2)$; $k_\rho = \frac{\rho_n}{\rho_m}$ – scale of air densities; ρ_n, ρ_m – air density at flight altitudes H_n, (m) of a full-scale aircraft and H_m, (m) of an FDSM $(\mathrm{kg/m}^3)$.

It should be noted that already in formulas (1) the dependence of scales k_M and k_I on flight altitudes H_n of a full-scale aircraft and H_m of FDSM can be implicitly seen. The formulas (1) do not give the same dependence for the scale k_ℓ. Furthermore, there is no reason to claim that the flight altitudes of H_n and H_m are aerodynamic similarity altitudes for all modeling problems.

The geometrical parameters of the FDSM and, consequently, the scale k_ℓ are influenced by [6]:

1. Modeling problems, together with similarity conditions and a system of relations between the parameters of an FDSM, a full-scale aircraft, and the environment.
2. Design conditions concerning the provision of an internal volume sufficient for the placement of on-board equipment and component parts within the contour of the FDSM ($k_\ell \leq k_{\ell\ max}^{pl}$), as well as ensuring the possibility of adjusting the position of the CM and mass-inertia parameters of the FDSM (if $k_\rho \leq k_\rho^{adj}$).
3. Technological limitations taking into account the capabilities of the FDSM parts manufacturing methods (for example, waviness and roughness of the skin surface) and linkage of technological equipment ($k_\ell \leq k_{\ell\ max}^{tech}$).
4. Flight-technical requirements taking into account the method of bringing an FDSM to the flight regime required for the research, parameters, and characteristics of a particular carrier ($k_{\ell\ min}^{FTR} \leq k_\ell$, $k_{M\ min}^{FTR} \leq k_M$).
5. Operational limitations taking into account the need to ensure the convenience of working with an FDSM during ground tests, preparation for test and research flights, and repair ($k_{\ell\ min}^{op} \leq k_\ell \leq k_{\ell\ max}^{op}$).

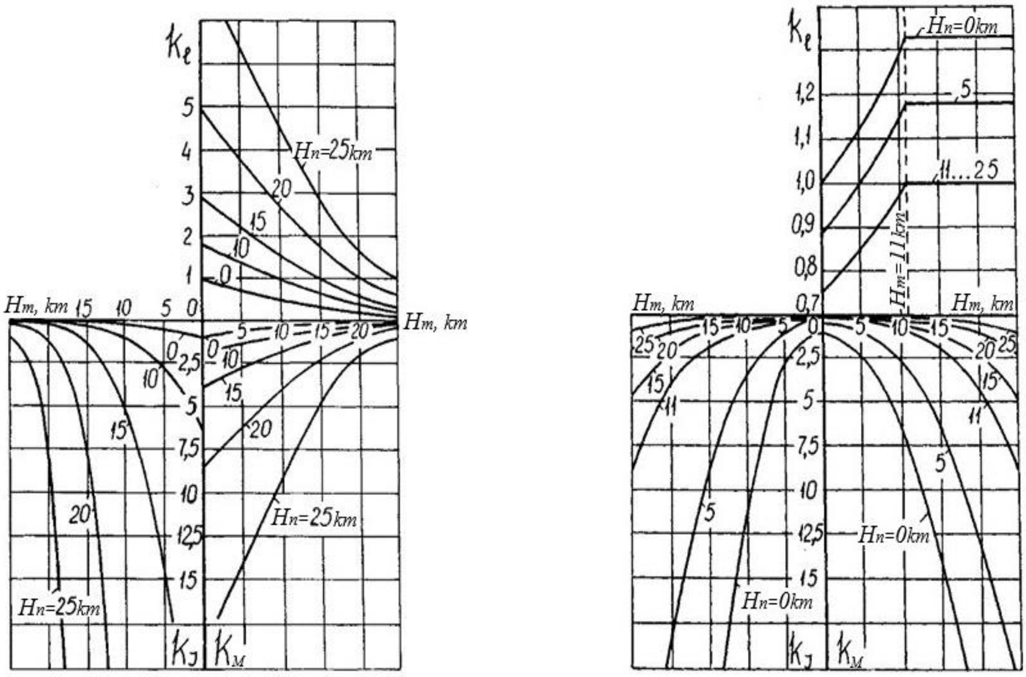
It should be noted that the scale k_ℓ depends on the accepted similarity criteria (Froude Fr, Reynolds Re and Mach M), which define aerodynamic similarity and include the similarity of force interactions of airflows with streamlined bodies, and also express certain requirements for the physical properties of the medium of the considered full-scale and modeled flow. The influence of the similarity criteria is not uniform in any particular case of motion, so there is practically no need for simultaneous satisfaction (corresponding equality) of the Fr, Re and M criteria. However, studies have established the mandatory Fr criterion similarity in flight dynamics modeling. Therefore, when modeling the flight of full-scale aircraft on FDSM, the following combinations of similarity criteria are possible [7-9]:

1. At the same time, the similarity conditions on Fr, Re and M criteria are satisfied. Under Standard Atmosphere (SA) conditions, this is only possible at $H_n = H_m$ and scales $k_\rho = 1$, $k_\ell = 1$, $k_M = 1$ and $k_I = 1$, which means that the external contours, masses, moments of inertia and position CM of a full-scale aircraft and an FDSM are identical. However, FDSM can be made of different materials, have different structural and power schemes and on-board equipment. Such FDSM allow to research practically all flight regimes of full-scale aircraft.
2. The similarity condition is satisfied only by the Fr criterion at auto-modelity according to the criteria Re and M. This is the only combination of criteria in which the choice of scale k_ℓ does not depend on the heights of the aerodynamic similarity H_n and H_m. However, after selecting the scale k_ℓ and assigning the H_n and H_m, the scales k_M and k_I are uniquely determined by relations (1).
3. The similarity conditions according to criteria Fr and Re at auto-modelity according to the criterion M. At this combination of similarity criteria:

$$k_\ell = \sqrt[3]{\frac{\nu_n^2}{g_n} \cdot \frac{g_m}{\nu_m^2}}; \quad k_M = \frac{\nu_n^2 \cdot \rho_n}{g_n} \cdot \frac{g_m}{\nu_m^2 \cdot \rho_m}; \quad k_I = \left[\frac{\nu_n^2}{g_n} \cdot \frac{g_m}{\nu_m^2}\right]^{\frac{5}{3}} \cdot \frac{\rho_n}{\rho_m}, \tag{2}$$

where ν_n, ν_m – coefficients of kinematic viscosity of air at altitudes H_n and H_m, $(\mathrm{m^2/s})$; g_n, g_m – acceleration of gravity altitudes H_n and H_m, $(\mathrm{m/s^2})$.

Using the SA, by formulas (2) it is possible to plot graphs on dependences of k_ℓ, k_M and k_I on aerodynamic similarity heights H_n and H_m (Fig. 2, a), which are necessary for operative solution of design problems of FDSM.



a b

Fig. 2. Graphs of dependences k_ℓ, k_M and k_I on aerodynamic similarity altitudes H_n and H_m: at satisfaction of similarity conditions according to criteria Fr and Re at auto-modelity according to criterion M (a) and according to criteria Fr and M at auto-modelity according to criterion Re (b)

As a rule, there is more than one pair of aerodynamic similarity altitudes (H_n, H_m), for which the scales k_ℓ, k_M and k_I have acceptable values. AN FDSM with such scales is physically feasible and capable of investigating a certain flight regime or maneuver of a full-scale aircraft. At the same time, the flight altitude of a full-scale aircraft (at a fixed value of scale k_ℓ) corresponds to a single value of the flight altitude of an FDSM, i.e., there is only one pair (H_n, H_m).

4. The similarity conditions according to criteria Fr and M at auto-modelity according to the criterion Re. At this combination of similarity criteria:

$$k_\ell = \frac{T_n}{T_m}; \quad k_M = \frac{T_n^3 \cdot \rho_n}{T_m^3 \cdot \rho_m}; \quad k_I = \frac{T_n^5 \cdot \rho_n}{T_m^5 \cdot \rho_m}, \tag{3}$$

where T_n, T_m – temperature of incoming airflow at altitudes H_n and H_m, (K).

Similarly to the previous combination of similarity criteria using the SA, but using formulas (3) it is possible to plot and use graphs of the dependencies k_ℓ, k_M and k_I on the aerodynamic similarity altitudes H_n and H_m (Fig. 2, b).

The number of pairs of aerodynamic similarity altitudes (H_n, H_m) is determined by the accepted scale of k_ℓ, and the range of flight altitudes of the FDSM. In this combination, as in the previous one, the flight altitude of a full-scale aircraft (at a fixed value of scale k_ℓ) corresponds to a single value of the flight altitude value of an FDSM, i.e., there is only one pair (H_n, H_m).

According to the above, it follows that when pairwise combinations of similarity criteria are satisfied, the scales k_ℓ, k_M, k_I is limited and can take the following values [1, 5]:

a) at $0 \le H_n \le 11000$ m, $0 \le H_m \le 11000$ m

- for the combination of Fr and Re

$0{,}52 \le k_\ell \le 1{,}93$; $0{,}47 \le k_M \le 2{,}14$; $0{,}128 \le k_I \le 7{,}97$,

- for the combination of Fr and M

$0{,}75 \le k_\ell \le 1{,}33$; $0{,}124 \le k_M \le 7{,}93$; $0{,}07 \le k_I \le 14{,}03$;

b) at $0 \le H_n \le 25000$ m, $0 \le H_m \le 25000$ m

- for the combination of Fr and Re

$0{,}12 \le k_\ell \le 8{,}34$; $0{,}049 \le k_M \le 19{,}97$; $0{,}0007 \le k_I \le 1389$,

- for the combination of Fr and M

$0{,}75 \le k_\ell \le 1{,}33$; $0{,}014 \le k_M \le 71{,}51$; $0{,}008 \le k_I \le 126{,}5$.

Experiment altitudes have their limitations due to the capabilities of the launch system as well as the technical capabilities of the braking and soft-landing system of FDSM. This fact is taken into account by introducing appropriate limits on the scale values k_ρ, determined by the permissible range of altitudes of the experiments.

In the case of satisfying only the Fr criterion (i.e., at modeling a given area of flight regimes, and, therefore, its coverage by the area of modeling flight regimes of a full-scale aircraft) the values k_ρ are determined by the inequality [5]:

$$\frac{\rho_n(H_{\min n})}{\rho_m(H_{\min m})} \le k_\rho \le \frac{\rho_n(H_{\max n})}{\rho_m(H_{\max m})}, \tag{4}$$

where $\rho_n(H_{\min n})$, $\rho_n(H_{\max n})$ – air density at minimum $H_{\min n}$, (m), and maximum $H_{\max n}$, (m) flight altitudes of the full-scale aircraft specified for the research, ($\mathrm{kg/m^3}$); $\rho_m(H_{\min m})$, $\rho_m(H_{\max m})$ – air density at minimum $H_{\min m}$, (m) and maximum $H_{\max m}$, (m) flight altitudes of an FDSM, ($\mathrm{kg/m^3}$).

When criteria Fr and Re or Fr and M are satisfied together (i.e., when modeling specific flight regimes or maneuvers of full-scale aircraft), the limits of k_ρ are determined by the inequality [5]:

$$\frac{\rho_n(H_{\mathrm{as.}n})}{\rho_m(H_{\min m})} \le k_\rho \le \frac{\rho_n(H_{\mathrm{as.}n})}{\rho_m(H_{\max m})}, \tag{5}$$

where $\rho_n(H_{\mathrm{as.}n})$ – air density at the flight altitude of the full-scale aircraft assigned for simulation, ($\mathrm{kg/m^3}$).

In case of simultaneous fulfillment of all basic airflow similarity criteria (Fr, Re and M) k_ℓ =1, k_ρ =1.

In the final determination of the limits of possible value scales k_ℓ ($k_{\ell\, min} \leq k_\ell \leq k_{\ell\, max}$) and k_ρ ($k_{\rho\, min} \leq k_\rho \leq k_{\rho\, max}$), all constraints imposed on them are taken into account.

We investigate the question of changing m_m with an increase in the linear sizes of FDSM (i.e., decreasing k_ℓ from $k_{\ell\, max}$ to $k_{\ell\, min}$).

When all basic airflow similarity criteria (Fr, Re and M) $k_\ell = 1$, $H_n = H_m$, $k_M = 1$, $k_I = 1$. The values of linear sizes, mass, and moments of inertia of the FDSM in this case are uniquely determined, and the designer has no possibility to vary them.

In case two of the three similarity criteria (Fr and Re or Fr and M) are satisfied, a decrease in k_ℓ leads to decrease in k_M and k_I, i.e., an increase in the linear sizes of the FDSM (according to relations (1)–(3) or graphs in Fig. 2, a and 2, b) entails in increase in its required mass and moments of inertia. It is also important that a decrease in k_ℓ (at $H_n = const$) leads to the need to perform modelling experiments at higher altitudes H_m. The cases under consideration allow for modeling within the auto-modelity zones both a certain mode ($V_n = const$ at $H_n = const$), and specified maneuvers with velocity change ($V_n = var$ at $H_n = const$).

Satisfying only the Fr makes it possible to modeling within the auto-modelity zones according to the Re and M criteria both a certain mode ($V_n = const$ at $H_n = const$) and specified maneuvers with altitude or velocity changes ($V_n = const$ at $H_n = var$ or $V_n = var$ at $H_n = const$), as well as a limited area of flight regimes ($V_n = var$ at $H_n = var$) of a full-scale aircraft. This follows from the independence of the scale k_ℓ from the altitudes H_n, and H_m, and from the fact that the same values of k_ρ can be achieved for different pairs (H_n, H_m).

Suppose that there is a range of values of the scale k_ρ. Then for any of these values (according to relations (1)), a decrease in the scale k_ℓ leads to a decrease in the scales k_M and k_I, i.e., to an increase in the required values of mass and moments of inertia of the FDSM. The minimum required values of mass and moments of inertia are achieved for the pair $k_{\ell\, max}$, $k_{\rho\, max}$. If the "descent" carried out in the k_ℓ from $k_{\ell\, max}$ to $k_{\ell\, min}$ (outer cycle) and by scale k_ρ from $k_{\rho\, max}$ to $k_{\rho\, min}$ (inner cycle), then the first value of the mass m_m satisfying the constraints will be minimum required (the moments of inertia will also be minimum), and the k_ℓ scale value – maximum. Further downscaling of k_ℓ or k_ρ, at best, only the same value of the required mass of an FDSM can be obtained.

Since mass is usually taken as the objective function in the design of an FDSM, in order to achieve its minimum, one should strive to create an FDSM with the minimum linear sizes, since an increase in the overall sizes of an FDSM inevitably entails an increase in its required mass [5].

4. METHOD FOR PREDICTING THE FLIGHT CHARACTERISTICS AND RESEARCH CAPABILITIES OF FDSM OF AIRCRAFT

When designing FDSM, equality of possible and required values of main parameters, satisfaction of flight-technical requirements for FDSM are achieved, and then a special method is used to predict the flight characteristics and research capabilities of FDSM of aircraft.

Its essence consists in the following: calculation of altitude-velocity limitations of flight characteristics of the FDSM, construction of the model flight regime area (MFRA) and its analysis (Figs. 3, 4); displaying of the MFRA into the area of modelling aircraft flight regimes (AMAFR); comparison of AMAFR with flight regimes specified for the research from the aircraft flight regime area (AFRA); analysis of the results, and formation of a conclusion about the capabilities of the FDSM as a research tool.

The result of calculation and analysis of the MFRA is a conclusion about the design altitude-velocity characteristics of an FDSM with a specific set of main parameters, but the conclusion about its capabilities as a research tool is made only after construction of the AMAFR.

Each point (V_m, H_m) of the MFRA in the coordinate system OV_mH_m characterizes a certain altitude-velocity flight regime of an FDSM, and the point (V_n^*, H_n^*) of the AMAFR in the coordinate system $OV_n^*\mathrm{H}_n^*$ – a certain altitude-velocity flight regime of a full-scale aircraft, which, in principle, can be researched on an FDSM with the considered set of main parameters.

Any curve in coordinates OV_mH_m, limiting the MFRA, is displayed in coordinates $OV_n^*H_n^*$ by corresponding curve-limitation of the AMAFR. The procedure of displaying the MFRA into the AMAFR consists of the transition from the MFRA in coordinate system OV_mH_m to the AMAFR in the coordinate system $OV_n^*\mathrm{H}_n^*$ and is performed using the scale value k_ρ and the SA by the formulas [5]:

$$H_n^* = f(\rho_n^*) = f\left(k_\rho \rho_m(H_m)\right); \qquad V_n^* = V_m\sqrt{k_\ell \frac{g_n^*}{g_m}}, \tag{6}$$

where ρ_n^*, g_n^* – air density and acceleration of gravity at the altitude H_n^*, (m) of a full-scale flight, $(\mathrm{kg/m^3})$.

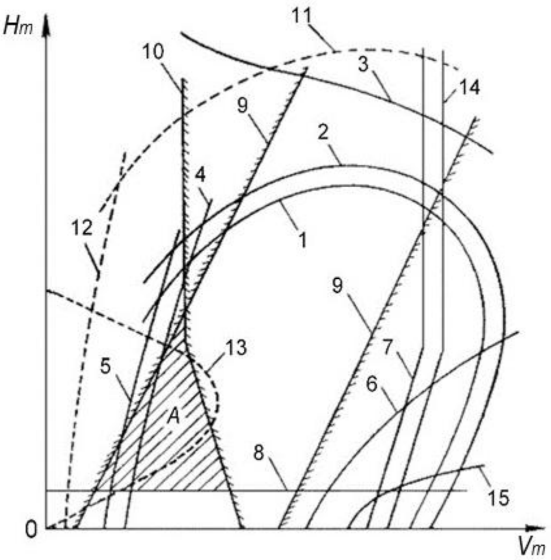


Fig. 3. System of altitude-velocity limitations of MFRA [5]: 1 – by maximum velocity of steady horizontal flight; 2 – by planning speed; 3 – by critical dive velocity; 4 – by minimum velocity of steady horizontal flight; 5 – by stall velocity; 6 – by maximum permissible velocity head; 7 – by aerodynamic heating limit temperature; 8 – by minimum permissible flight altitude; 9 – by dynamic similarity conditions with respect to auto-model values of Reynolds criterion Re; 10 – by dynamic similarity conditions with respect to auto-model values of Mach criterion M; 11 – by maximum carrier flight velocity; 12 – by minimum carrier flight velocity; 13 – by maximum flight velocity at ground launch; 14 – by engine operating conditions; 15 – by maximum operational overload; A – example of the area of possible researches at auto-modelity by criteria Re and M

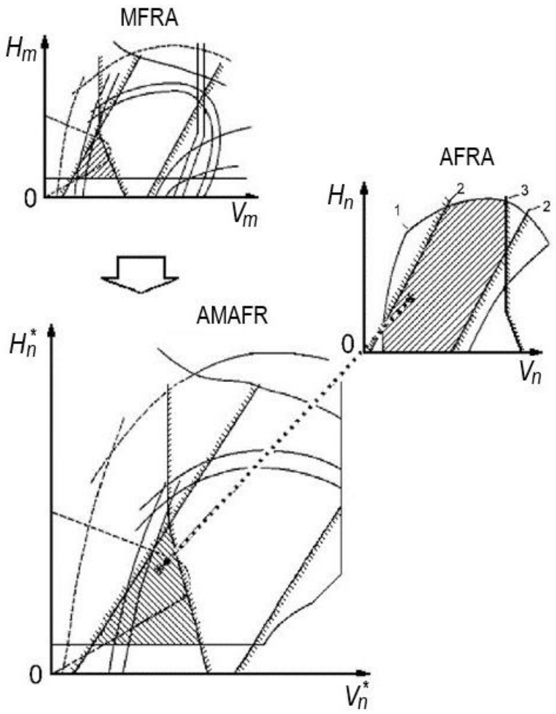


Fig. 4. Scheme for determining the capabilities of an FDSM as a research tool [5]: 1 – limits of AFRA; 2 – limits of auto-modelity zone on the AFRA according to the criterion Re; 3 – limits of auto-modelity zone on the AFRA according to the criterion M

Using the display procedure, the AMAFR is determined, which is directly compared with the regimes specified for research from the AFRA, since the scales in the coordinate systems $OV_n^* H_n^*$ of the AMAFR and $OV_n \mathrm{H}_n$ of the AFRA are the same.

Based on the results of this comparison, a conclusion is made about the possibilities of researching the aircraft flight regimes specified in the project task on its FDSM with a specific set of main parameters. The final selection of the main parameters of the FDSM is carried out as a result of optimization by mass m_m, which is both a parameter of the FDSM and an objective function.

5. CONCLUSIONS

The work is carried out from the standpoint of analysis, improvement, and generalization of the existing theoretical and methodical foundations of creating FDSM. This, to a certain extent, made it possible to fulfill the goal of the work – to reduce the time and cost of creating aircraft by improving the accuracy, informativeness, and efficiency of flight research results on FDSM. The paper does not consider all the features of creating FDSM but shows the influence and dependence of altitude-velocity limitations of physical modeling tasks on the main parameters of FDSM of aircraft.

At the same time, a literature review was conducted to study and analyze the achievements and problems of aircraft flight physical modeling, the theoretical and methodological foundations of creating FDSM, and the conduct of flight studies on them. It was determined that the method of researching aircraft flight characteristics on free flying dynamically similar models is widely used in the practical activities of aviation institutes and firms.

In the paper presented herein, the conditions and scales of similarity used in creating FDSM and conducting flight studies on them are considered. The influence on the main parameters of FDSM of modeling tasks, together with the similarity conditions and the system of relations of parameters of FDSM, of the full-scale aircraft and the environment; design conditions; technological limitations; flight-technical requirements; operational limitations is emphasized. A specific method for predicting flight characteristics, and research capabilities of FDSM using a unique display procedure is developed and presented.

When discussing programs performed or being carried out in aviation institutes and firms, it should be noted that information about the theoretical foundations of creation, design features, technology of production of FDSM and flight studies, as well as other features of this promising method in the open press, is limited [8-10]. And, nevertheless, it is possible to assert with confidence that the results of theoretical studies of the authors presented in the paper are in good agreement with the results of similar studies of scientists dealing with the problems of modeling the dynamics of aircraft flight in the Earth's atmosphere.

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