Problems of ensuring the acceleration dynamics of aircraft during track tests at a speed of 1600 m/s

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Abstract: *The article discusses the problems that arise when creating new models of supersonic and hypersonic aircraft, which can be solved by model high-speed ground track tests. Mathematical modelling of the aerodynamic characteristics of an aircraft (test object) placed on a rail carriage and accelerated by the solid fuel rocket engines is performed. The numerical method solves the problem of the motion of a body of variable mass along a rail track. To determine the required length of the rail track, a mathematical model of the ballistic characteristics of the upper stage of the rocket carriage was compiled, calculations were made, and the influence of various factors on achieving the maximum speed of the test object was analysed. An analysis is made of the influence of the total mass of the carriage with the load and engine thrust on the possibility of accelerating the test object to the Mach speed (4-5).*

Key Words: *hyper sound, impact waves, rocket rail track, technical area*

1. INTRODUCTION

The development of promising hypersonic aircraft for various purposes is one of the most relevant technical areas of our time. The propulsion system (PS) for such aircraft can be a ramjet-turbojet power plant integrated with a solid fuel rocket engine (SFRE), or with a liquid rocket engine (LRE). In the United States, Pratt & Whitney, Rocketdyne, and Boeing, together with the teams of the US Air Force Research Laboratory (AFRL) and the Defense Advanced Research Projects Agency (DARPA), created the X-51A supersonic combustion ramjet using the JP-7 fuel [1]. The US Pentagon considers hypersonic flights as “the new Stealth technology”. Aircraft of this type are practically invulnerable to air defense systems because of their high speed, and significantly reduce the time for striking at a long-range target. According to experts, a new generation of combat cruise missiles, spacecraft, as well as military and civilian airliners will be created based on this technology.

Over the past 10 years, the Pentagon has spent more than two billion dollars on hypersonic technology. In Russia, the hypersonic flying laboratory (GLL) “Kholod” was created. The developer of the GLL “Kholod” is the Baranov Central Institute of Aviation Motor Development. Firms of Russia (MKB “Fakel”, Turaevo Machine-building Design Bureau “SOYUZ”, Chemical Automatics Design Bureau, MAI and others) and Kazakhstan (National Center for Radio Electronics and Communications, Al-Farabi Kazakh National University) participated in the creation of the GLL “Kholod” and in conducting hypersonic flight experiments. CIAM conducted most of the hypersonic flight experiments under contracts with firms of France (ONERA, Aerospatiale, SNECMA-SEP) and the United States (NASA) [1]. A significant reduction in financial costs in the study of hypersonic key technologies, according to the authors, would be to conduct preliminary studies of a number of problems that arise in aircraft at hypersonic speeds, and to develop new solutions and technologies based on model tests on an experimental ground power unit.

2. TASKS SOLVED BY FULL LEVEL RANGE OPERATIONS

The greatest uncertainty in the use of well-known techniques in the design of aircraft and propulsion systems, as well as their conjugation, arises when calculating distributed aerodynamic loads at flow regimes close to separated state, as well as in determining acoustic loading, thermal effect and aerothermoelastic phenomena. In addition, it is possible to thematically highlight the problems that arise when creating hypersonic aircraft [2], [3], [4], which could be worked out through model tests on a rocket rail track at high Mach numbers.

In the field of thermodynamics:

– determination of the conditions for the transition of the laminar boundary layer into turbulent one;

– interaction between impact waves and the boundary layer, determination of the conditions for separation of the boundary layer;

– the interaction of normal, oblique impact waves reflected from various structural elements, their interference on heat-loaded glider elements, such as a nose, leading edges, etc., when testing aircraft elements of a real configuration;

– effects arising from a multiengine power plant and affecting the aerodynamic characteristics of aircraft;

– effects of real gas upon entering a dense atmosphere, including testing of materials and coatings.

In the field of gasdynamic:

– organization of flows in the internal gasdynamic paths of a supersonic combustion ramjet with a subsonic and supersonic combustion, as well as the study of the possibility of organizing combustion in two modes [5], [6];

– tests of model hydrocarbon ramjet, using the reaction of kerosene conversion in order to increase thrust momentum and to cool structural elements;

– testing a model supersonic combustion ramjet with the aim of ensuring maximum efficiency of the fuel combustion process, as well as taking into account real processes in air intakes, combustion chambers and nozzles (starting and stability).

In the field of flight dynamics:

– development of the fin and control elements of hypersonic aircraft taking into account real aerodynamic loads and heating;

– study of the effect of trim changes when switching engines at high speeds.

In the field of improving ramjet propulsion systems:

– development of working processes of combined ramjet with liquid rocket engine or with solid fuel rocket engine [5], [6], [7];

– development of processes in supersonic inlets with a fixed angle of the compression wedge in order to reduce thermal loads on structural elements;

– integration of a combined installation with hypersonic aircraft;

– selection of the optimal supersonic combustion ramjet based on the analysis of physicochemical processes during fuel combustion in high-speed air flows;

– the introduction of composite materials and a decrease in the specific gravity of the engine;

– increase in specific impulse due to the efficiency of fuel combustion;

– studies of working processes in ramjet with an increase in flow rate to numbers 5-6 M when using hydrocarbon fuel.

In the field of improving the design, materials and thermal protecting:

– tests of heat-resistant coatings and materials, including composite ones;

– tests of coatings providing protection of the aircraft surface from oxidation, moisture adsorption and to increase the strength of the surface layer of thermal protecting.

In the field of flight tests:

– checking the operability of new engines in conditions simulating a real flight;

– study of the possibilities of controlling ramjet productivity;

– verification (and testing) of structural elements in the conditions of ramjet flight and mechanization;

– checking the effectiveness of integration of the airframe and combined propulsion system with ramjet.

The experience gained in testing aircraft objects on earlier modifications of the “Rocket Rail Track 2500” installation allows us to optimistically consider the possibilities of modelling and solving the above problems. The financial costs of conducting such full level tests are massively smaller than the corresponding full level flight tests. A limitation of track full level studies is the short duration of the experiment at high speeds of the test object. Experimentally we worked out the design of the 33AB-HO-53 carriage to accommodate the test object and propulsion system. Acceleration to speeds of 3 M and higher is also provided by the mastered design of propulsion system with solid fuel rocket engine. Mathematical modelling and the development of an algorithm for the numerical solution of a problem that simulates test conditions precede the practical implementation of aircraft track tests. An analysis is carried out to determine the incremental linking of the test object with propulsion system. One calculation example is given below.

3. BRIEF DESCRIPTION OF THE ROCKET RAIL TRACK

The vertical profile of a rail track can be divided into three sections. The first section, intended for acceleration of test objects, ascending with an oblique angle equal to $= 1.15°$ $(tan\ \alpha = 0.02)$, $(2cm$ of rise per 1 linear meter of track). At the end of the track, part of the path has a downward profile designed to brake the carriage with the test object. Between the two sections, there is a segment of the path with a rounding profile.

Propulsion system: the drive of the test object on the bench rail track is carried out by an accelerator of solid fuel rocket engines (SFRE), placed on the rail speed carriage. In this example, the test object is a certain abstract aircraft with a streamlined shape. Their mass characteristics and geometric dimensions are given. Figure 1 shows an image of the layout of the rail carriage with the test object and SFRE.

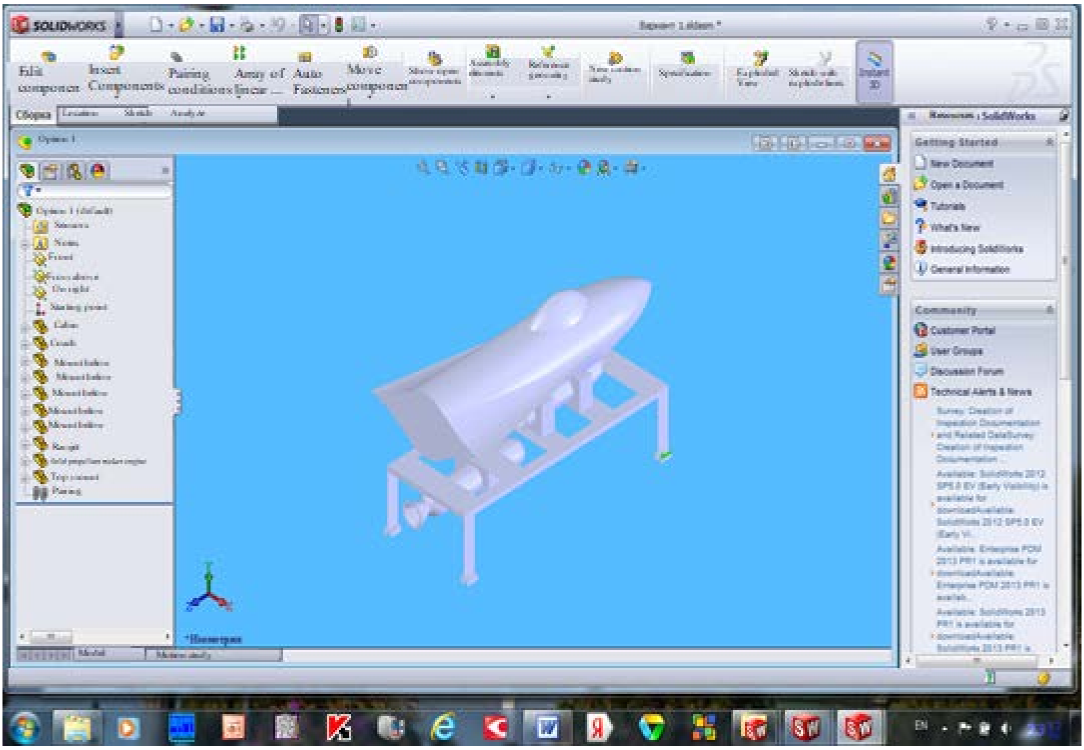

Fig. 1 – Isometric. The carriage with the test object and propulsion system with solid fuel rocket engine

The task is posed: it is necessary to determine the required engine thrust in order for the test object to reach speeds of up to $4\,M$ and evaluate the effect of the mass and geometric dimensions of the test object and the propulsion system on flight dynamics. Suppose that the center of air pressure is in line with the center of gravity of the mobile device (coupling the carriages to the engines and the test object) of the rail track. The center of resulting force application from the engine thrust is also on this line. Then the thrust force is directed at an angle $\alpha > 0$ to the horizontal due to the inclination of the rail track. The force of weight acting vertically can be decomposed into two components: tangential and normal to the trajectory of movement.

4. BALLISTIC TEST MATHEMATICAL MODEL

The equation of motion of a mobile device can be represented as:

$$m_{\Sigma}(t)\frac{dW_c(t)}{dt} = \Sigma P(t) - \Sigma R_{aer}(t) - \Sigma R_{fr}(t) - R_d(t) - R_{wav}(t), \tag{1}$$

where $W_c(t)$ is the current speed of the rail carriage; $m_{\Sigma}(t)$ is the total mass of the carriage with the test object and the propulsion system with a fuel supply or the total mass of the mobile device; $\Sigma P(t)$ is the overall thrust; $\Sigma R_{aer}(t)$ is the resulting force of aerodynamic drag; $R_d(t)$ is the vertical projection of the gravity of the device; $\Sigma R_{fr}(t)$ is the overall friction force; $R_{wav}(t)$ is the wave drug.

Carriage speed is defined as:

$$W_c(t) = \frac{dx}{dt}, \tag{2}$$

where x is the current coordinate (length) of the rail track.

During supersonic motion, the aerodynamic drag consists of three types of drag caused by friction, vortex activity, and impact waves [5]. The drag coefficient depends on the shape of the device, Mach and Reynolds numbers. It is usually determined by a wind-tunnel test of model. Friction drag is the sum of the frictional drag force of the carriage shoes, which depends on the pressure force normal to the rails, and the drag force, which depends on the side surface of the device and the windstream Reynolds number:

$$X_{fr}(t) = C_f S_{lat} \frac{\rho W_c^2}{2}, \tag{3}$$

Here, the coefficient of friction can be represented by empirical data from [5], [6]. At Reynolds numbers $Re < 10^6$, the coefficient is:

$$C_f = \frac{0{,}074}{Re^{0{,}2}}, \tag{4}$$

For large Reynolds numbers $Re > 10^6$:

$$C_f = \left(\frac{0{,}242}{lgRe}\right)^2, \tag{5}$$

The coefficient of friction drag is recalculated through the ratio of the lateral surface to the mid-section area:

$$C_{x\,fr} = C_f \frac{S_{lat}}{S_{\text{M}}}, \tag{6}$$

The supersonic wave drag of a device of this configuration cannot be calculated; it can only be determined experimentally. Equations (1-6) can be converted to a form convenient for calculations:

$$\frac{dW_c(x)}{dx} = \frac{\sum P(x)}{m_\Sigma \times W_c(x)} - \frac{R_{aer}(x)}{W_c(x)} - \frac{\text{g} \sin \alpha}{W_c(x)} - \frac{\mu\, \text{g} \cos \alpha}{W_c(x)}, \tag{7}$$

Wave and base losses, as well as losses due to vortex activity, can be approximately estimated by increasing the drag coefficient. Equation (7) is solved by the fourth-order Runge-Kutta numerical method, while the entire length of the rail track is divided with an equal step of 1 m.

The algorithm of the dynamic task of accelerating the test object is represented by a system of equations:

1. The total mass of the mobile device is summed from the mass of 2 carriages, the mass of 4 solid fuel rocket engines and the mass of the test object:

$$m_\Sigma(t) = \sum m_{car}(t) + m_{SF1}(t) + m_{SF2}(t) + m_{SF3}(t) + m_{SF4}(t) + m_{to}, \tag{8}$$

2.The mass of the solid fuel rocket engine consists of the mass of the structure and fuel:

$$m_{SF} = m_{SF\,str} + m_{SF\,fuel}\,(t), \tag{9}$$

3. The mass of the mobile device decreases when parting the carriage No 2 with the spent fuel SFRE 1 and SFRE 2:

$$m_{car} = m_{car1} + m_{car2\,acc}\,(t), \tag{10}$$

4. The solid fuel burning velocity:

$$\dot{m}_{burSF} = \frac{dm_{SF}(t)}{dt} \tag{11}$$

5. Accelerator thrust force:

$$\mathrm{P}_1\,(t) = \mathrm{P}_{SF1} + \mathrm{P}_{SF2}. \tag{12}$$

6. The maximum value of traction force:

$$P_2(t) = P_{SF1} + \mathrm{P}_{SF2} + \mathrm{P}_{SF3} + \mathrm{P}_{SF4}. \tag{13}$$

7. The thrust of the engines placed on the carriage No 1:

$$\mathrm{P}_3\,(t) = \mathrm{P}_{SF3} + \mathrm{P}_{SF4}. \tag{14}$$

8. Drag force:

$$R_{aer}(t) = C_{x\,RED} \times \frac{\rho W^2}{2} F_\Sigma\,, \tag{15}$$

where F_Σ is the total mid-section of the mobile unit, $C_{x\,RED}$ is the reduced drag coefficient taking into account frontal and wave losses, vortex activity losses, base drag.

9. Loss of thrust to overcome gravity:

$$R_y(t) = \mathrm{m}_\Sigma \times \mathrm{g} \times \sin\alpha, \tag{16}$$

where α is the angle-of-attack.

10. Friction losses in the carriage support:

$$R_{fr}(t) = \mu \times m_\Sigma \times \mathrm{g} \times \cos\alpha, \tag{17}$$

where μ is the coefficient of friction between the shoe of the carriage and the rail.

11. The dynamic equation of motion:

$$\frac{dW_{CX}}{dx} = \frac{P}{(W_{CX} \times m_\Sigma)} - \frac{R_{aer}}{(W_{CX} \times m_\Sigma\ \ )} - \frac{\mathrm{g} \times \sin\alpha}{W_{CX}} - \frac{\mu \times \mathrm{g} \times \cos\alpha}{W_{CX}}\ . \tag{18}$$

12. The relationship of the time of movement of the object with the coordinate of the rail track:

$$d\tau = \int_0^x \frac{W_{CX}}{dx}, \tag{19}$$

$$dx = \int_0^t W_{CX}\,dt. \tag{20}$$

The total mass of carriages with engines and fuel $m_\Sigma(t)$ changes when the carriage moves due to fuel burnup and when the accelerator is parted. The rate of change in the mass of fuel is determined by the rate of combustion of the fuel in the combustion chambers of the engines [6], [7]. The drag forces to the movement of the rail carriage are made up of the total aerodynamic losses, losses to create lift and to overcome friction. Time in the dynamics equation is excluded, i.e. the equation of motion is transformed in such a way as to bind the current variable values of the speed W_C(x) and mass m_Σ(x) of the plant to the length of the rail track.

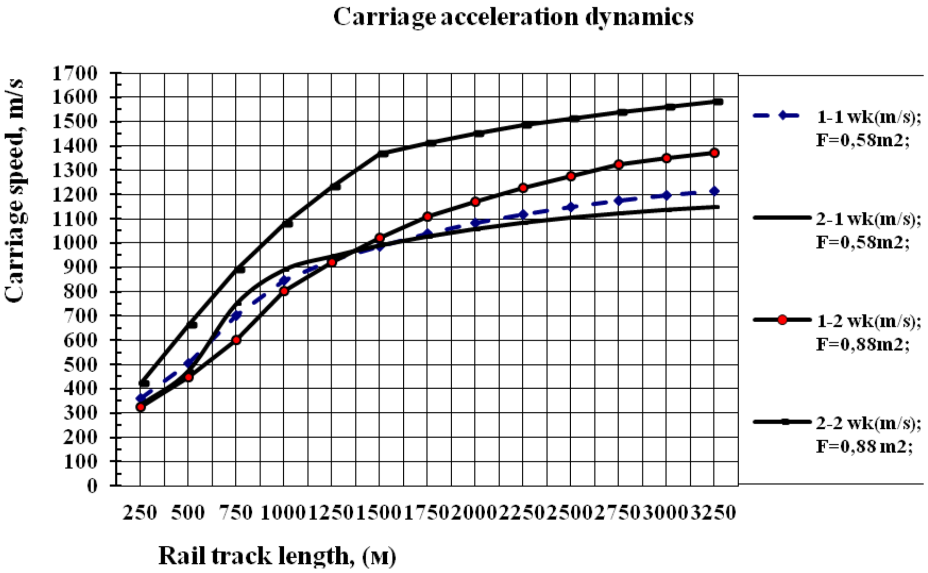

Fig. 2 – Speed graphs of the accelerated object at various points on the rail track depending on the placement of a different number of engines on carriages

Figure 2 shows the speed of the test object at various points on the rail track. The following scenarios are considered in which the placement of one or two identical engines varies:

– option 1-1, this is a coupler of 2 rail carriages, on which one solid fuel rocket engine with a thrust of $470\ kN$ and a mass of $610\ kg$ is placed. The mass of carriages is $100\ kg$, the test object weighing $350\ kg$;

– option 2-1, on the 1st rail carriage-accelerator, two solid fuel rocket engines are placed, and the second one carries one solid fuel rocket engine;

– option 1-2, on the first rail carriage-accelerator, one solid fuel rocket engine is placed, and the second one carries two solid fuel rocket engines;

– option 2-2, 4 solid fuel rocket engines, two are placed on each carriage.

The charge of solid fuel is designed for a burning time of $1.9\ s$. The first carriage provides acceleration to a certain speed and when the fuel burns out to the remainder of $30\ kg$ it is disconnected from the hitch. Further acceleration is provided by the engines (or engine) of the second carriage. From the graph, it follows that the layout drawing of engines 2-1 is the most disadvantageous. In this case, the object quickly accelerates to a speed of $900\ m/s$ and travels a distance of $1000\ m$, but then the acceleration becomes much slower due to gasdynamic losses. This dependence almost coincides with the scheme 1-1, the initial mass of which is less than $610\ kg$, and slightly less than the mid-section of the equipped hitch. Scheme 1-2 is significantly different in the final version from the considered ones, although acceleration in the initial section to $100\ m$ is realized more slowly, but the total thrust of two engines provides a significant increase in speed. Scheme 2-2 is more preferable, since mass characteristics, thrust and aerodynamic losses are successfully combined.

The influence of aerodynamic losses is presented in the graphs shown in Figure 3. The scenario for calculating the movement of rail carriages according to the 2_1_1 scheme (one solid fuel rocket engine in each of the two carriages) provides for the acceleration of the hitch to the level of $1000\ m$. The initial total weight of the hitch is $1770\ kg$. Further, the carriage No 1 is parted, and the acceleration of the object with the carriage No 2 is carried out by one solid fuel rocket engine.

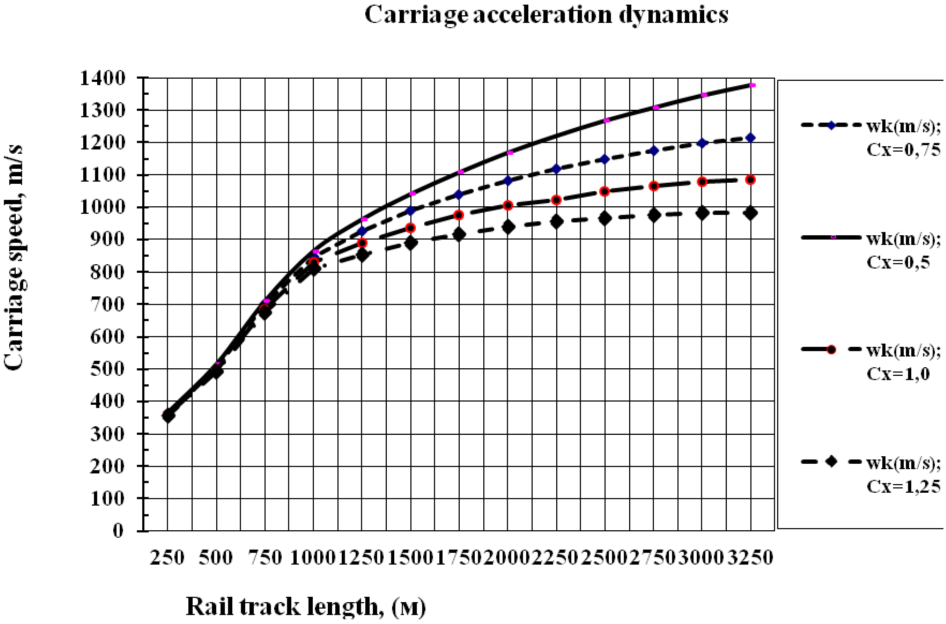

Fig. 3 – Dependences of the speed of the carriage with the test object weighing $350\ kg$, accelerated by a hitch of two carriages with one solid fuel rocket engine on each. For different values of drag coefficient

Since losses from all types of drag are recounted through C_x, this coefficient can be determined only based on tests. In the calculations, the drag coefficient varied in the range $C_x \sim 0.75 - 1.25$. The lower values correspond to the estimates obtained from the experiments, and the upper ones are somewhat overestimated and in this case are the limiting estimates of aerodynamic losses. Figure 3 shows that all graphs have a kink at the track point corresponding to $1000\ m$. At this point, the accelerator carriage is parted.

Comparing the curves characterizing the total aerodynamic losses, it can be noted that at speeds up to $2.5\ M$ all the dependences practically merge and at speeds above $3\ M$ there is a significant difference. Aerodynamic losses become comparable with the thrust, and their positive difference determines the pace (inclination of the dependence) of further acceleration. Since the aerodynamic losses at the speed of the object $M \sim 4$ are $R_{aer} = 349285\ H\ (C_x = 0.75)$ and $R_{aer} = 424126\ H\ (C_x = 0.85)$, i.e. the difference between thrust and aerodynamic drag is small. Losses associated with the presence of a positive incidence R_y are equal to $R_y = 10^5 N$. Since the incidence angle is constant, and the mass of the power plant during movement decreases due to fuel production, this estimate is the maximum. Losses caused by the friction forces of the carriage shoes on the track rails are also in order of magnitude $R_{fr} = 0.5 \times 10^3 N$

in flight and $R_{fr} = 0.1 \times 10^5 N$ at the beginning of acceleration. In general, these losses have almost no effect on the dynamics of acceleration of such a power plant.

Considering that an increase in the thrust of a solid fuel rocket engine is associated with a further increase in the total mass of equipment, this way of improving the efficiency of the track unit is limited. To achieve a speed of $(5-6)M$ during track tests, it is necessary to look for ways to significantly reduce aerodynamic losses by reducing the unit mid-section and improving the streamlined appearance of the test object with a carriage.

For example, by appropriately arranging objects on a rail carriage to organize oblique impact waves. To reduce vortex activity, it is desirable for the rail carriage itself to have streamlined shape. It is also possible to control the position of the impact waves, reducing interaction with impact waves reflected from the carriage. On the surface of the streamlined body, it is possible to organize the boundary layer suction or by injecting gas along the lateral surface to organize vortex activity and other events. The total mass of equipment of the moving part of the track unit is very significant and requires coordination with the magnitude of the thrust. The influence of the mass of equipment on the dynamics of acceleration of the test object is illustrated by the graphs shown in Figure 4.

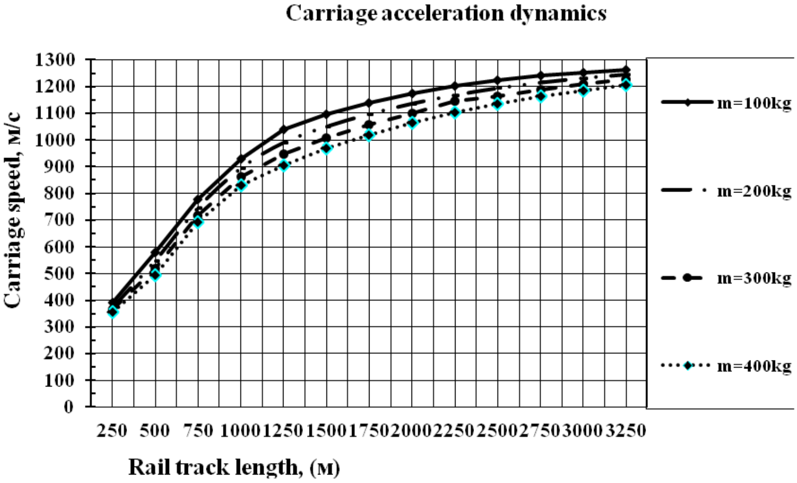

Fig. 4 – The effect of the mass of the test object on the acceleration speed of the carriage along the length of the rail track

The dependence of the speed of the carriage with the test object on the mass of the test object is almost linear, as can be seen from formula (7), since the losses taken into account by the last members of the formula are small compared with aerodynamic losses. This calculation is an overestimation, because the mid-section of the experimental device was defined as a simple sum excluding the screening of the accelerator by the test object. In general, the influence of the test object's mass on the final speed is not so significant, since the proportion of the changed mass is from 12% to 36% based on the final section of the track; the rest of the mass is on the propulsion system and equipment.

In general, the weight and size characteristics of the rail carriage significantly affect the dynamics of acceleration of the test object. A separate issue is the organization of rational aerodynamic flow around the entire mobile installation. Only by applying a set of measures: optimizing the thrust of the propulsion system, weight, and dimensions of the unit, as well as reducing aerodynamic losses (reducing C_x), you can achieve a speed of $7\,M$. From the calculations, we can conclude that the track length of $3.5\ km$ is sufficient to solve most of the problems noted earlier [8], [9], [10], [11], [12], [13], [14]. Due to the higher Earth level atmospheric compared with altitude conditions, it is possible to simulate full level aerodynamic loads on the test object at hypersonic speeds.

5. CONCLUSIONS

The problems faced by developers of hypersonic aircraft and ramjet engines require their consistent solution through full level range operations. The most economical of all possible implementations are tests of aircraft and ramjet on a rocket rail track. To determine the required length of the rail track, a mathematical model of the ballistic characteristics of the upper stage of the rocket carriage was compiled, calculations were made, and the influence of various factors on achieving the maximum speed of the test object was analyzed. We perform estimates of the required thrust of engines placed on a rail carriage to ensure the speed of the test object up to $1600\ m/s$ with the considered mass and dimensions.

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