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Особенности достижения предельных значений скорости трековых испытаний летательных аппаратов баллистического типа

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Разработка высокоскоростных летательных аппаратов баллистического типа со скоростью, превышающей 1000 м/с, в настоящее время является приоритетной задачей за рубежом и в России. Эффективность таких новых изделий подтверждается трековыми испытаниями со скоростью их применения. Испытательные полигоны с рельсовыми трассами существуют практически во всех странах, например в США их более 15: двухрельсовые, монорельсовые и различные их комбинации, различающиеся длиной, шириной рельсовой пары, рельсами и конструкцией самого трека, включая герметичную оболочку над рельсовой дорожкой для заполнения ее более легкой средой. Самый длинный трек США Hollotan AFB, расположенный в New Mexico, длиной 15536 м. Располагают трековыми полигонами с различной длиной и своим особенным исполнением Англия, Франция, Германия, Канада, Италия, Япония, Индия, Китай, Корея, Турция и другие страны, включая Африканский континент. Высокоскоростные полигонные испытания в России проводятся на экспериментальной установке «Ракетный рельсовый трек 2500», размещенной на территории ФКП «ГкНИПАС имени Л. К. Сафронова». Экспериментальная установка состоит из рельсового пути, размещенного на специальном основании, обеспечивающем необходимый вертикальный профиль пути с участками подъема и прямолинейного горизонтального движения, а также технологический участок снижения для торможения подвижного технологического оборудования. Испытуемое изделие размещается на ракетной трековой каретке, движущейся по рельсам на опорах скольжения. Для придания ускорения трековой каретке используются ракетные двигатели твердого топлива, тяга которых выбирается на основе баллистических расчетов для достижения требуемой скорости испытания. Длина трека играет важную роль для достижения предельных скоростей разгона подвижного трекового снаряжения. Огромное аэродинамическое сопротивление, пропорциональное квадрату скорости движения каретки при испытаниях на высоких скоростях приводит к необходимости уменьшать мидель и массу подвижной установки. Увеличение тяги двигателей приводит к росту массы и стоимости трекового снаряжения, а также к необходимости увеличения запаса прочности опор скольжения. Однако прирост скорости испытаний можно достичь при замене воздушной среды газами, обладающими существенно меньшей плотностью, например гелием. Трековые испытания новых летательных аппаратов или их элементов хотя и дешевле летных испытаний, однако достаточно дороги. В этой связи работа по теоретической оценке замены среды из окружающего воздуха на гелий, а также на смеси гелия с воздухом при разной его концентрации в крытой галерее на трековой рельсовой дорожке является новой, актуальной и практически полезной задачей. В работе выполнено численное моделирование задачи сверхзвукового обтекания потоком смеси гелия с воздухом при различном их объемном соотношении. Получены численные значения аэродинамического сопротивления при скорости движения ка-

ретки равной 830 м/с. Приведены результаты численных расчетов динамики движения 3D-модели монорельсового трекового снаряжения, которые планируются для использования при проведении натурных огневых экспериментов.

Ключевые слова: трековые испытания, ракетная каретка, собственные частоты, гелиевая среда, вибрационное ускорение, спектральная плотность.

Features of reaching limiting speed values of track tests of ballistic type aircraft

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The development of high-speed ballistic aircraft with speeds exceeding 1000 m/s is currently a priority abroad and in Russia. The effectiveness of new such products is confirmed by track tests at the speed of their use. Test sites with rail tracks exist in almost all countries, for example in the USA there are more than 15 of them. Double-rail, monorail and various combinations thereof, differing in length, width of the rail pair, rails and the design of the track itself, including a sealed shell over the rail track to fill it with a lighter one environment. The longest track in the USA is Holloman AFB, located in New Mexico with a length of 15536 m. They have track ranges with different lengths and their own special design in England, France, Germany, Canada, Italy, Japan, India, China, Korea, Turkey and other countries, including African continent. High-speed range tests in Russia are carried out on the experimental installation "Rocket Rail Track 2500", located on the territory of the FSE "Scientific test range of aviation systems named after L.K. Safronov". The experimental installation consists of a rail track placed on a special base, providing the necessary vertical profile of the track with sections of ascent and straight horizontal movement, as well as a technological descent section for braking moving technological equipment. The product under test is placed on a rocket track sled moving along rails on sliding supports. To accelerate the track carriage, solid fuel rocket engines are used, the thrust of which is selected based on ballistic calculations to achieve the required test speed. The length of the track plays an important role in achieving the maximum acceleration speeds of moving track equipment. The enormous aerodynamic drag, proportional to the square of the speed of movement of the carriage, when tested at high speeds, leads to the need to reduce the midsection and mass of the mobile unit. An increase in engine thrust leads to an increase in the weight and cost of track equipment, as well as to the need to increase the safety margin of sliding supports. However, an increase in test speed can be achieved by replacing the air medium with gases that have a significantly lower density, for example, helium. Track testing of new aircraft or their elements, although cheaper than flight testing, is quite expensive. In this regard, work on the theoretical assessment of replacing the medium from ambient air with helium, as well as with a mixture of helium and air at different concentrations in an indoor gallery on a track rail track, is a new, relevant and practically useful task. The work performed a numerical simulation of the problem of supersonic flow around a helium-air mixture at different volumetric ratios. Numerical values of aerodynamic resistance were obtained at a sled speed of 830 m/s. The results of numerical calculations of the motion dynamics of a 3D model of monorail track equipment, which are planned for use in conducting full-scale fire experiments, are presented.

Keywords: Track tests, rocket sled, natural frequencies, helium medium, vibration acceleration, spectral density.

Introduction

Helium, out of all known gases, reveals the best combination of properties suitable for use in testing conditions on a track table. First, helium and its mixtures with air are not toxic. Secondly, helium has a low molecular weight, low density and low viscosity. Its gas constant under normal conditions (NC) is equal to R = 2077.2 J/(kg K); density (NC) ρ_{he} = 0.1785 kg/m^3 7.264 times less than air density; dynamic viscosity ν_{He} = 19 μPa s; heat capacity Cp = (5.2 – 5.27) kJ/(kg °C); thermal conductivity coefficient λ = 0.15 W/(m K); volume kmol He μV = 22.42 m3/kmol, adiabatic index k = Cp / Cv = 1.67.

We demonstrate the covered section of the track (hereinafter we will call it a helium gallery or tunnel) in the form of a cylinder of radius $R_т$ and length L, cut in half lengthwise. The tunnel volume will be equal to the gallery volume $V_г$ and the volume of the hydrodynamic flume made along the tunnel $V_л$ below the horizon level

$$V_Г = \int_0^L S_Г(x)\,dx\,, \tag{1}$$

here $S_г(x)$ – cross-section of the above-ground section of the covered gallery.

$$V_Л = \int_0^L S_Л(x)\,dx\,, \tag{2}$$

here $S_Л(x)$ – cross-section of a section of the hydrodynamic tray of a covered gallery located below the level of the base of the rail track.

Area volume $V_г$ with gallery length L = 600 m Rт = 1,75 m can be simplified presented as

$$V_Г = \frac{\pi}{2} R_Т^2 \cdot L = 2886{,}336 \text{ m}^3. \tag{3}$$

Gas volume occupied by a tray with dimensions of a rectangular profile width b = 1 m, depth h = 1 m

$$V_Л = b \cdot h \cdot L = 600 \text{ m}^3.$$

When filling the gallery with helium, we assume that the air, a denser gas, located in the tunnel will be forced out through the tray and leave for the atmosphere. Considering the high cost of helium, it is necessary to estimate the required amount of helium for testing with different concentrations of the air-helium environment, then carry out simulation numerical calculations in order to determine the optimal concentration of the air-helium environment to achieve the maximum effect of reducing aerodynamic drag and increasing the speed of the track carriage with the object tests at a fixed thrust of a solid propellant rocket engine (SPRE). The results of the theoretical forecast are subsequently subject to validation after the construction of an indoor gallery and fire technological launches of the monorail equipment of the rocket sled with vibration measurements at a speed of 830 m/s.

It is necessary to prepare the environment in the gallery with different contents of helium mixed with air, starting from the case with a purely helium environment. To test in a 100% helium tunnel, there is no need to displace air with helium from the tray because the rail track is above the tray level. On the other hand, accelerating the track carriage to a speed of 2.5 M and its entry into a section with a modified environment is associated with the interaction of shock waves around the nose of the test object and shocks reflected from the surface of the rail track, as well as from the edge of the tray, which will inevitably cause mixing environment and unevenness of environmental parameters along the height of the gallery section. In this regard, it is advisable to provide for mixing air and helium in advance. Regarding the gallery environment in the form of pure helium, everything is not so complicated here. The only thing is that before launching, a chromatographic analysis should be performed at various points along the cross-section and length of the helium section.

The total volume of the helium gallery is approximately 3500 m^3. The required mass of helium to fill the corridor is equal to

$$N_{He} = V_\Sigma / \mu_v = 156{,}11 \text{ kmol},$$

$$m_{He} = M \cdot V_\Sigma / \mu_v = 624{,}91 \text{ kg}. \tag{4}$$

The sound speed in a helium medium is 965 m/s.

When a covered gallery with atmospheric air is filled with helium with a mass m_{He}, excess pressure will arise, it is determined by the dependence

$$p_{\text{B}} + p_{\text{He}} = \frac{m_{\text{B}}}{V_{\Sigma}} R_{\text{B}} \cdot T(K) + \frac{m_{\text{He}}}{V_{\Sigma}} R_{\text{He}} \cdot T(K)\,. \quad (5)$$

Mass being 625 kg, the excess total pressure is 2 ATM. Within the time, the pressure will equalize with atmospheric pressure, displacing air from the covered volume. Fig. 1 shows a photograph of a monorail track sled with a model test object.

Рис. 1. Изображение монорельсовой трековой каретки с модельным объектом испытания.
Состав: передний башмак с кронштейном для крепления модельного объекта испытания; РДТТ;
задний башмак

Fig. 1. Image of a monorail track sled with a model test object.
Composition: Front block with bracket for fastening a model test object; Solid propellant rocket engine; rear block

The thrust of the solid propellant boost engine provides the necessary acceleration to achieve the required test speed. If necessary, to increase thrust, the rocket sled (Fig. 1) can be composed of two solid propellant rocket engines, placed in the form of a train of several accelerator stages connected in series with the head instrument sled [1]. The brackets house automatic control elements and, if required, vibration acceleration sensors.

In the USA, on the basis of the Holloman track, with length of 15536 m, a special indoor tunnel was created to simulate the conditions of rarefied atmosphere, which can be filled with helium gas to reduce the aerodynamic resistance of the environment during testing [2; 3]. The length of the covered tunnel is 3353 m, and its diameter is 4.67 m.

The research purpose is to numerically simulate the gas-dynamic flow around a 3D model of moving track equipment in a tunnel filled with helium and helium-air mixtures in various concentrations. Flow calculations are carried out by a developed program using the Flow Vision complex [4–10], and the motion dynamics of a 3D model of a monorail rocket sled, developed by a program that takes into account the elastic structure of moving track equipment, schematized by the spatial arrangement of beams [11–13], with AMESim software package [14–19]. In both cases, there is a 3D model of a real rail track, including the vertical and horizontal profile of the track stand of the FSE "Scientific test range of aviation systems named after L.K. Safronov" and 3D track sled with a model test object (TS-TO).

The movement of the TS-TO system is considered at a supersonic speed of 846.8 m/s, approximately 2.5 M at 0.31 s, the carriage enters a tunnel filled with helium. The design thrust of the solid propellant rocket engine is assumed to be 4.3 t.s.

Fig. 2–4 show the simulation results, where the speed of the object's movement is presented in color [13].

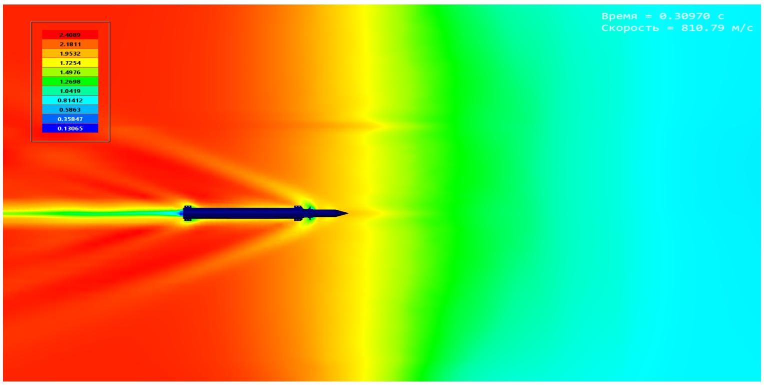

Рис. 2. Изображение обтекания воздушным потоком элементов трековой каретки
и объекта испытания перед входом в галерею с гелиевой средой. Вид сверху

Fig. 2. Image of the air flow around the elements of the track sled
and the test object before entering the gallery with a helium environment. View from above

Compaction shocks occur, when approaching the boundary separating two media: air and helium. Next, it presents the moment of entry of the TS-TO through the interface into the helium region. In this case, the angle of oblique shock waves increases when flowing around the elements of the track carriage with the test object when entering the helium environment.

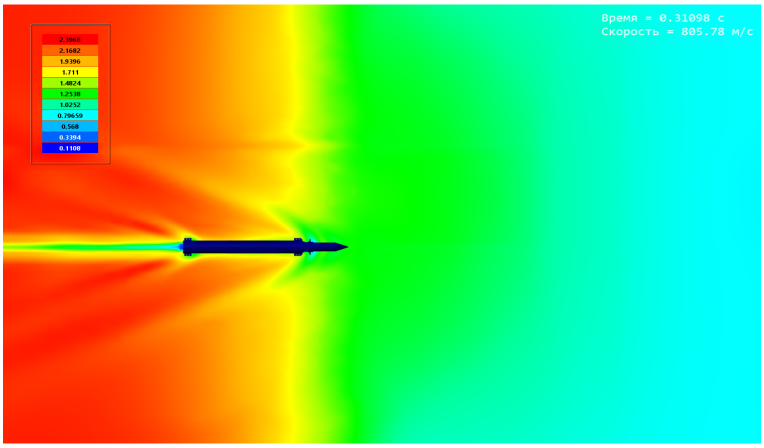

Рис. 3. Распределение скоростей среды на элементах ТК-ОИ
при прохождении начального участка с гелиевой средой

Fig. 3. Distribution of medium velocities on the TK-OI elements
when passing through the initial section with a helium medium

Fig. 3 demonstrates that the shock wave on the conical fairing of the test object is realized at a speed of 1.4 M, that is significantly less than the speed of movement of the sled itself of 2.5 M. This paradox is quite understandable. In a helium environment, the speed of sound at an external temperature of 20 °C is approximately 956 m/s, that is almost three times higher. The Mach number decreases sharply and the Mach angle increases. As the sled passes through the initial section with the helium medium, the geometry of the shock waves in the helium medium changes. The view represents the interference of direct shock waves with oblique ones. The physical picture of supersonic flow around conical bodies changes. The angle of the oblique shock wave in the helium medium on the conical fairing increases to 74–75 degrees.

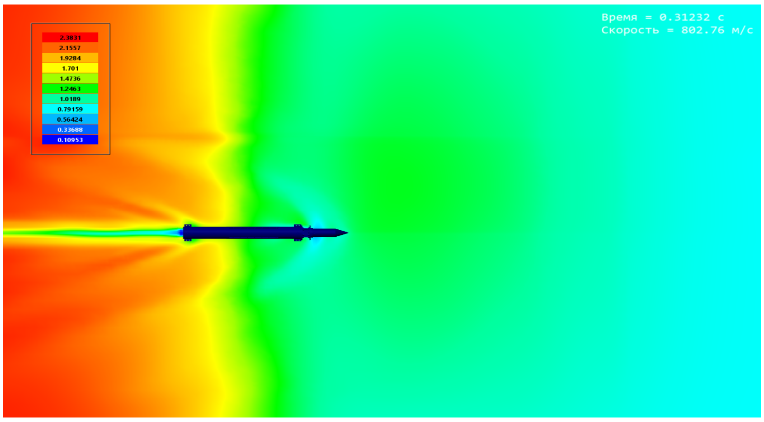

Рис. 4. Картина сверхзвукового обтекания элементов трекового подвижного снаряжения в воздушной и гелиевой среде. Вид сверху

Fig. 4. Picture of supersonic flow around elements of track moving equipment in air and helium. View from above

The image presents the Mach angles in the air flow, it is an acute angle approximately equal to 60° and a larger angle of 75–80° in a helium environment. Fig. 5. demonstrates the graphs illustrating the acting aerodynamic forces along the X, Y, Z axes on the track sled with the test object at a speed of 832 m/s.

When the TS-TO moves at a speed of 830 m/s, the lifting force directed upward along the Y axis is about 3100 N. The lateral force directed along the Z axis is 600–700 N. The frontal aerodynamic drag force is 22500 N. After 0.31 s, the product enters a tunnel with a helium atmosphere. In this case, the cone of the nose part breaks through the film and the TS-TO enters the atmosphere with helium. An impact disturbance occurs, followed by attenuation of the force action, and the aerodynamic forces decrease sharply. Therefore, the aerodynamic drag force decreases almost 10 times to a value of 2600 N. However, when entering a section with a helium medium, the track sled receives a disturbance (similar to a shock), but with the opposite sign of the force action. Acceleration disturbance resulting from a stepwise dip in aerodynamic drag. The transient process is simultaneously superimposed with calculated oscillations caused by the computational numerical adaptation of the grid.

The results of modeling the entry of a monorail track sled into the helium section of the track show the significant impact of reducing aerodynamic drag. The wave pattern of interaction between the surface of the TS-TO track moving equipment changes, namely, a series of shock waves changes its configuration. The Mach cone angle increases, the configuration of the bow shock takes on the form of a direct shock wave, characteristic of a lower speed of flow around structural elements. The wave resistance changes proportional to the product of the density of the medium and the speed of sound in a given medium. The structure of the boundary layer changes when the flow moves around the cone of the head part and especially the interface between the cone and the cylinder of the head fairing of the test object. Fig. 6 exhibits the influence of the density of the medium in a gallery containing different percentages of the air-helium mixture on the aerodynamic drag coefficient of the TS-TO dynamic system.

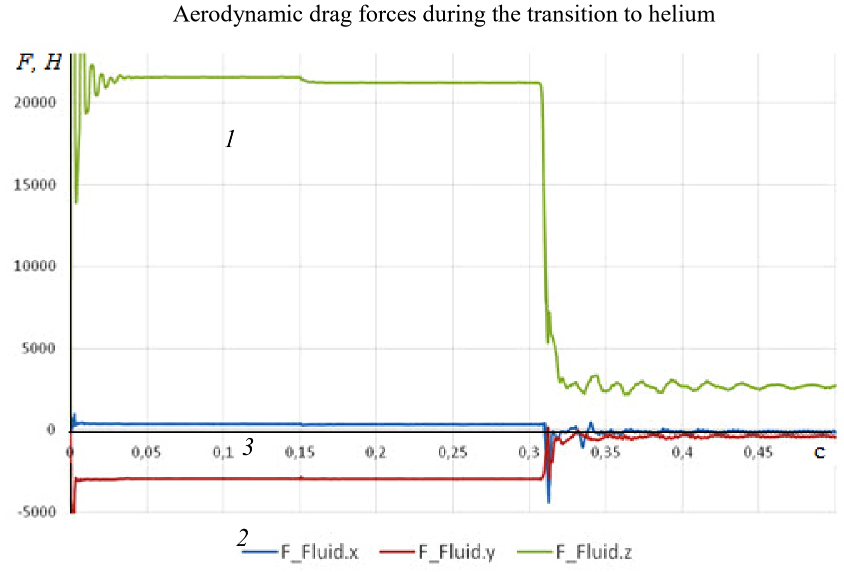

Рис. 5. Графики, иллюстрирующие изменение действующих сил по осям X, Y, Z на поверхность 3D-модели трековой каретки с объектом испытания при вхождении в гелиевый участок трека при скорости 830 м/с: *1* – сила аэродинамического сопротивления по оси X (зеленый цвет); *2* – вертикальная ось Y (красный цвет); *3* – Z на графике отражает поперечную боковую нагрузку (синий цвет). По оси абсцисс время в с

Fig. 5. Graphs illustrating the change in the acting forces along the X, Y, Z axes on the surface of a 3D model of a track sled with a test object when entering the helium section of the track at a speed of 830 m/s: aerodynamic drag force along the X axis – green; Y – (red) vertical axis; Z – on the graph reflects the transverse lateral load (blue color). The x-axis reflects time in s

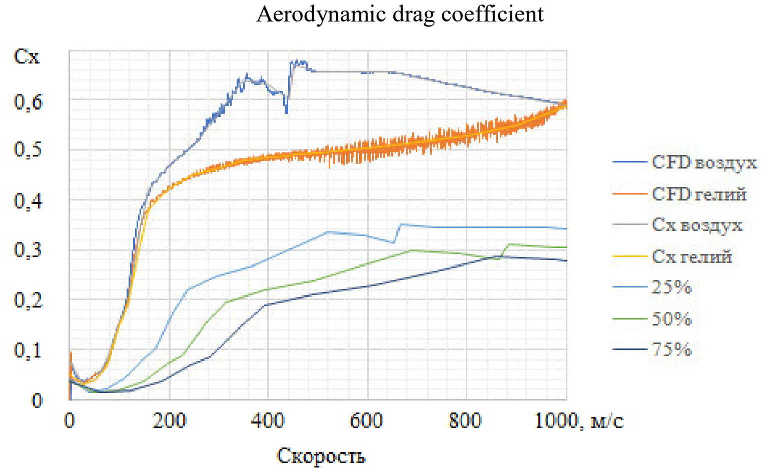

Рис. 6. Графики зависимостей коэффициентов аэродинамического сопротивления от скорости движения трековой каретки при разной концентрации смеси воздуха и гелия

Fig. 6. Graphs of the dependencies of aerodynamic drag coefficients on the speed of movement of the track sled at different concentrations of the air and helium

Fig. 7 exhibits the influence of the density of the medium in the tunnel containing different percentages of helium on the increase in the acceleration rate of the TS-TO system.

Fig. 7 demonstrates when accelerating a track sled with a test object at the considered total mass of equipment and solid propellant thrust is equal to 43 kN, a speed of 830 m/s is achieved, and with a mixture of air and helium in an equal proportion of 50 % by volume, the speed is achieved 1000 m/s. In a helium environment, the speed will be already 1120 m/s.

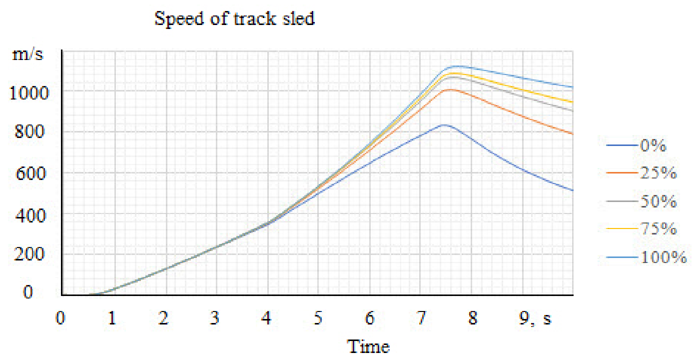

Рис. 7. Влияние процентного содержания воздуха в смеси с гелием
в составе среды галереи на величину предельной скорости разгона каретки

Fig. 7. Influence of the percentage of air mixed with helium in the gallery
environment on the maximum acceleration speed of the sled

When tested in air at a maximum speed of 800 m/s, the lifting force acting on the rocket track sled structure is 3200 N. The magnitude of the lifting force during testing is important because the friction forces when the blocks slide along the contact surface of the rail depend on it. When helium is added to the gallery air in a ratio of 50 % by volume, the lift at maximum speed is reduced to 2700 N compared to a purely air environment. Increasing the helium in the mixture to 70 % reduces the lifting force of the sled to 2000 N. And in a gallery filled only with helium, the lifting force at a maximum speed of 800 m/s decreases to 500 N. The reason for the nonlinear dependence of the influence of helium in the mixture with air at low concentrations is subject to further analysis. The lateral force directed along the Z axis also decreases as the concentration of helium in the air in the indoor gallery medium increases from 200 N (medium is air) to 90 N (medium is helium). Lateral force arises from the asymmetry of the track's relief. During monorail testing, the track carriage is located on the right rail, with horizontal relief on the right, and a hydraulic tray located below the horizon on the left. Figure 8 shows the calculated values of the aerodynamic drag force during the movement of the track sled depending on the density of the medium in the gallery at different percentages of helium in the air.

The maximum value of the aerodynamic drag force of the air environment is 23000 N during the launch of the TS-TO system. With a 50 % mixture of air and helium, the resistance of the medium at maximum sled speed is reduced to 10,000 N. In the clean environment with helium, the resistance is minimal and equal to 6500 N. The friction forces of the blocks on the contacting surfaces of the rail head also turn out to be dependent on the environment. Therefore, in a purely air environment, their maximum value is –3600 N, and, on the contrary, in a helium environment, the friction forces do not exceed –700 N. The yaw angle torque behaves in a similar way. It varies, like all aerodynamic forces, during movement. Its maximum value in air is 20000 Nm, corresponding to the maximum acceleration speed, and in helium it is less than 5000 Nm. The maximum value of the pitch angle torque in air is +2800 Nm, and in helium does not exceed +600 Nm. The calculated values of vibration accelerations on the front and rear blocks without taking into account the actual deviations of the rail track from straightness along the X axis do not exceed 2 m/s^2. However, the frequency range of the spectrum of maximum values of vibration accelerations of the rear block is wider - from 3 to 70 Hz, while in the front block the maximum vibration accelerations are realized at frequencies from 3 to 40 Hz. We would like to highlight that the first resonant frequency of the blocks along the X and Y axes, determined by vibration testing, is 3.15 Hz. It is not possible to isolate the influence of the density of the air-helium mixture medium on the density of the vibration acceleration spectrum of the blocks along the X axis, since all the curves merge into one picture. Also, the difference is practically indistinguishable for the density of the spectrum of vibration accelerations along the X axis of the track sled body and the fairing of the test object. The calculated spectrum of vibration accelerations along the Y axis on the blocks is characterized by resonances in the range from 3 to 120 Hz, with a maximum at a frequency of 70 Hz. The front block has a resonance at 15 Hz with the highest vibration acceleration amplitude, and then decreasing peaks of vibration overload amplitudes are realized at the following frequencies: 26, 47, 75, 98 Hz, and so on. Along the Y axis, a decrease in the density of the greenhouse environment leads to a decrease in the amplitudes of vibration overloads both on the blocks and on the sled body and the test object, that is, it reduces the maximum vibration accelerations by almost 2.5–3 times, and the damping effect is more pronounced on the rear support. For example, Fig. 9 shows graphs of the density distribution of vibration acceleration spectra by frequency for the nose cone along the Y axis.

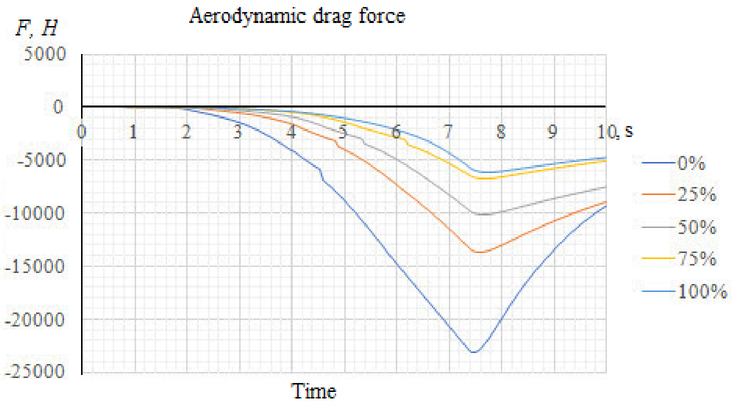

Рис. 8. Графики зависимостей сил аэродинамического сопротивления от объемного содержания гелия в среде галереи при разгоне каретки с объектом испытания

Fig. 8. Graphs of the dependencies of aerodynamic drag forces on the volumetric content of helium in the gallery environment during acceleration of the sled with the test object

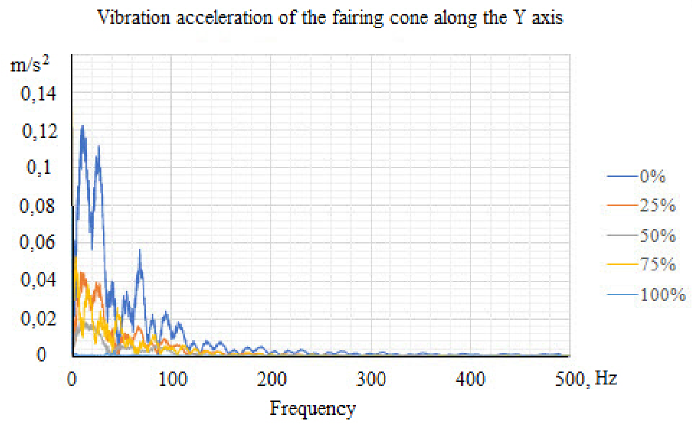

Рис. 9. Зависимости плотности спектра ускорений по оси Y обтекателя объекта испытания

Fig. 9. Dependencies of the density of the acceleration spectrum along the Y axis of the fairing of the test object

The density of the vibration acceleration spectrum along the vertical Y axis of the conical fairing of the test object has a maximum of 0.12 m/s2 at a frequency of 5–7 Hz. Further resonant peaks occur at the following frequencies 20–25; 47; 76 Hz, and others. The highest values of vibration overload are realized in air, the lowest are in helium. The vibration overloads of the sled body along the Y axis are somewhat less pronounced than those of the fairing, and the frequencies corresponding to the maximum vibration accelerations are shifted to the region of higher frequency values, and significant values are distributed in the range of up to 250 Hz. The maximum density values of the vibration acceleration spectrum of 0.3–0.35 m/s^2 of the fairing of the test object along the Z axis have a significantly smaller frequency range of 25–32 Hz. It is not possible to isolate the influence of the density and viscosity of the medium in the calculations.

The maximum effect of increasing the acceleration speed of the track sled is expected in a helium environment. The costs of arranging a track gallery and acquiring the required mass of helium can be reduced by choosing a rational length of the gallery according to the calculated graphs from Fig. 10, while achieving the planned effect of increasing the maximum acceleration speed of the dynamic TS-TO system.

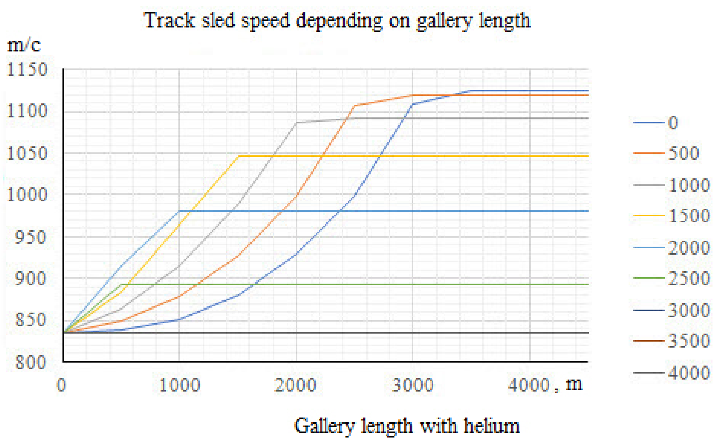

Рис. 10. Графики зависимостей прироста скорости системы ТК-ОИ от длины галереи со средой гелия

Fig. 10. Graphs of the dependencies of the speed increase of the TS-TO system on the length of the gallery with a helium medium

Conclusion

Taking into account the high cost of helium and the need for its availability in large quantities to conduct full-scale experiments, calculation estimates were obtained for choosing the length of the indoor gallery and the expected increase in the acceleration rate of the dynamic TS-TO system at different helium concentrations. The effect of reducing the density of the medium due to mixing air with helium in a closed gallery becomes significant already at 50 % helium concentration. As an option, we can recommend conducting experiments to validate the obtained calculated results at a 50% concentration of a helium-air mixture in the gallery environment.

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