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G. I. SOKOL[1], Doctor of Technical Sciences, Prof.
orchid.org 0000-0002-6183-9155
E-mail: gsokol@ukr.net
V. S. KOZIN[2], Candidate of Technical Sciences, Senior Research Fellow
orchid.org 0000-0002-7876-142X
E-mail: vako@email.ua

[1] Oles Honchar Dnipro National University
72, Nauky Ave., Dnipro, 49010 Ukraine
[2] Institute of Technical Mechanics of the National Academy of Sciences of Ukraine and State Space Agency of Ukraine
15, Leshko-Popelya Str., Dnipro, 49005 Ukraine

ASSESSMENT OF THE POSSIBILITY OF INTRODUCING A SOLID PROPELLANT ACCELERATOR P230 OF THE ARIANE 5 ROCKET AS A HELMHOLTZ RESONATOR

The problem of harmful resonant pressure fluctuations in solid-propellant accelerators during the initial acceleration of the Ariane 5 space system is considered. An assumption was made regarding the connection of these fluctuations with changes in the geometric characteristics of the P230 accelerators due to the formation of cavities in them according to the burnout regimes filled with solid rocket propellant combustion products. The volumes of cavities formed during propellant combustion were calculated. The engine scheme that arose after the first part of the charge burned out is considered. It is obvious that the shape of the cavity can be approximated by the Helmholtz resonator model. It is also taken into account that the gradual heating of the upper layers of solid propellant and the associated changes in the wave resistance of the propellant play a role in the appearance of pressure pulsations in the combustion chamber (CC) of a rocket engine. This leads to the rise of resonant phenomena in the formed cavities. As a result of considering various resonator systems, the Helmholtz resonator model, which is most suitable for the computational explanation of pressure pulsations, was chosen to describe the physical model of resonance phenomena. Calculations using this model yielded the same frequency as in the results of measurements during the flight operation of the Ariane 5 space system. Next, the direction for solving the problem of reducing resonant oscillations in the combustion chamber is proposed.

Keywords: *pressure, nozzle, wave resistance, pulsations, resonance, frequency.*

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Introduction. The existing problem is the occurrence of low-frequency pulsation pressure with the first-frequency mode from 20.0 to 22.0 Hz in the combustion chamber (CC) solid-propellant accelerators P230 of the Arian 5 rocket still does not find a calculated explanation [3]. Attempts to explain the cause of pressure pulsations by the flow of gas flow through an obstacle — the inner edge of the ring — of the thermal inhibitor in the combustion chamber did not give clear explanations [1]. In the thesis of Ausa Sekis [2], the physical principle of operation of a solid-propellant engine is characterized as based on the occurrence of oscillations in the Helmholtz resonator. But this characteristic is given declaratively.

Discussion of the problem. It is known [4] that at relatively low frequencies of pressure pulsations (up to 25 Hz), the law of the burning rate of solid rocket propellant (SRP) is written as $U\left(P\right)=U_1 \cdot P_к^{\nu}$, where $P_к^{\nu}$ is the pressure in the combustion chamber, U_1 is the preexponential, and $\nu < 1.0$ is the degree indicator. Despite this, it is possible to accept the law of the burning rate as quasistationary. Pressure pulsations during flight overloads lead to peeling of the heat-protective coating of the solid propellant rocket engine and are transmitted to the liquid components of the propellant in the tanks of the first stage of the Ariane 5 rocket, which flies in a package with two boosters [11]. Pulsating fluctuations of the liquid propellant lead to unstable power supply through the pipelines of the turbopump unit of the liquid rocket engine, and further to its unstable operation and pulsations of thrust and specific impulse. Therefore, the explanation of the oscillation excitation mechanism in this case does not raise doubts.

The purpose of the actual work is to develop a methodology that will make it possible to evaluate the presentation of the solid-propellant accelerator P230 of the Ariane 5 rocket as a Helmholtz resonator, to explain the occurrence of oscillations of a certain frequency and to develop measures to eliminate unstable engine operation. At the same time, the following tasks are solved:

• to consider the existing models describing the occurrence of oscillations of the P230 solid-propellant accelerator of the Ariane 5 rocket, identify the positive and negative sides of these methods;

• to propose a new physical model of the occurrence of oscillations based on the representation of cavities in the P230 accelerator by resonators;

• to propose a calculation model for determining the frequency range of oscillations based on the idea that the hollows formed during propellant burnout are approximated by a Helmholtz resonator.

The physical picture of charge burnout. It is known from [5, 13] that after the start, the thrust of the P230 accelerator increases from 540 tons at sea level to approximately 670 tons after 20 seconds of flight. Between 30 and 40 seconds, the upper segment of the solid propellant charge, divided lengthwise into 3 unequal parts by thermal inhibitors, completely burns out. This segment differs from the other two in the shape of the charge channel. This is a 15-ray star instead of the round channel of the others. Accordingly, the burning surface area of the first segment is larger, and the burning time is shorter. In addition, the first segment is only 3.5 meters long with a total charge length of 24.7 m [5, 13]. After the first segment burns out, the thrust of the accelerator decreases to approximately 400 tons and then returns to the level of 600 tons by the 110th second of flight. At this time, the pressure in the combustion chamber increases from 40 to 50 atm. At the place of the first segment of the charge, a void appears, filled only by gases of combustion products of SRP. The internal diameter of the circuit breaker housing is 3.05 m. In the other two segments of the charge with a circular channel, the solid propellant burns out at a speed of 7.4 mm/s.

Determination of the resonance amplitude based on the Helmholtz resonator model. After 60 seconds of flight, pressure pulsations occur in the combustion chamberwith the first oscillation frequency mode of 20.0...22.0 Hz and the second oscillation mode of 40.0...44.0 Hz. The amplitude of oscillations is rapidly increasing (see Figure 1) [3]. The moment of increase in amplitude is obviously due to the heating of the upper layers of solid rocket propellant. Such a process is known, for example, under the action of infrared radiation [9]. As the temperature of the SRP increases, the speed of sound in it slows down, and the wave resistance decreases. This, in turn, leads to a decrease in the frequency of pressure pulsations under conditions of a general increase in pressure in the combustion chamber. This is evidenced by the peeling of the

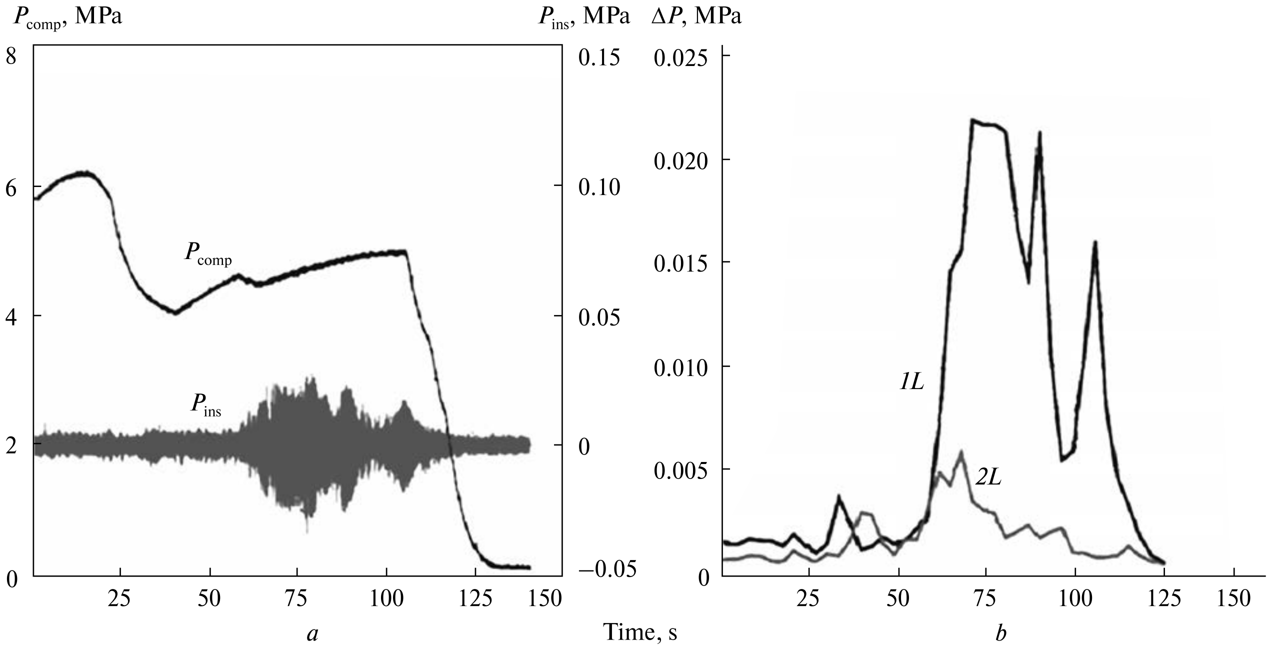

Figure 1. Dependence of the amplitude of pressure fluctuations on the flight time [3]

thermal protective coating (TPC). The speed of sound is related to wave resistance by the formula

$$Z = \rho \cdot C_{cep}, \quad (1)$$

where Z is wave resistance, kg/(m^{2}s), $\rho = 1770$ kg/m^3 — density of solid rocket fuel [13], C_{cep} — speed of sound in the environment — in this case SRP, m/s [10].

The oscillating speed of propellant particles at the boundary with the heat-shielding coating depends on the wave resistance

$$\dot{\xi} = \Delta P / \rho \cdot C_{cep}, \quad (2)$$

where the denominator is determined by formula (1), ΔP — pressure pulsations are equal to 0.025 MPa in the CC [3], $\dot{\xi}$ — is the oscillating speed of the medium particles.

For approximately similar solid rocket propellants, $C_{cep} \approx 41$ m/s, then $Z = 72570$ kg/m^{2}s. At $\Delta P = 0.025 \cdot 10^6$ Pa, $\dot{\xi} = 0.3425$ m/s. This speed at a frequency of $f = 20.0$ Hz and the resonance frequency $\Omega = f/2\pi$ — 125 rad/s corresponds to the amplitude of oscillations according to version [8]

$$\xi = \dot{\xi} / \Omega = 0.027 \text{ m}.$$

Let's look at the engine scheme formed after the first part of the series burned out. We can see the formation of resonators from the new dimensions of the hollow volumes. It can also be seen that the cavity has changed in shape so that it can be approximated by the Helmholtz resonator model. Then, you can use known relations from acoustics to determine the natural frequency of oscillations f [6, 8—10, 12]. We calculate f as follows [7]

$$f = \sqrt{\nu \cdot \frac{A^2}{m} \cdot \frac{P_0}{V_0}}, \quad (3)$$

where $\nu \approx 1.5$ is the adiabatic index of diatomic gases of SRP combustion products, $A = 0.63585$ m^2 — the area of the critical section of the nozzle, $m = 102.258$ kg — mass of gases of combustion products in the nozzle, $P_0 = 4.8 \cdot 10^6$ Pa — pressure in the hollow at the time of pulsations, $V_0 = 69.653$ m^3 — the volume of the hollow at the time of pulsations. To calculate the mass of gases in the nozzle block, the density of gases was determined using the Mendeleev-Clapeyron formula [6]

$$P = \frac{\rho}{\mu} \cdot R \cdot T_c, \quad (4)$$

where $T_c = 3600$ K, $\mu \approx 28$ kg/kmol — molecular weight of combustion products, R — is a universal gas constant. So, $\rho = (P \cdot \mu)/(R \cdot T_c) = 8.314$ kg/m^3 ≈ ≈ 8.31 kg/m^3.

The volume of the nozzle block was calculated as the volume of a truncated cone with dimensions: a length of 3.78 m, the diameter of the critical section of the nozzle of 0.9 m, and an exit diameter of 2.99 m [13]. The volume V_0 consists of the volume of the hollow of the first burned-out segment of 22.2725 m^3 plus the volume of the charge channel of the other two segments, taking into account the ignition of the channel of these charges at the time of the occurrence of pressure pulsations of 47.38 m^3. Finally, according to formula (3), we get $f = 20.21$ Hz.

Conclusions. The geometric model of propellant burnout in the SRP booster of the P230 accelerator made it possible to conclude that, in general, the chamber with hollows and propellant works like a Helmholtz resonator. Accordingly, to avoid the appearance of a low resonant frequency, it is necessary to either reduce the volume of the combustion chamber or increase the critical section of the Laval nozzle. The first is impossible. When increasing the critical section of the nozzle, the main criterion is to reduce the amplitude of pressure pulsations to an acceptable level without resonance phenomena.

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Г. І. Сокол[1], д-р техн. наук, проф.
orcid.org 0000-0002-6183-9155
E-mail: gsokol@ukr.net
В. С. Козін[2], канд. техн. наук, старш. наук. співроб.
orcid.org 0000-0002-7876-142X
E- mail: vako@email.ua

[1] Дніпровський національний університет імені Олеся Гончара
проспект Науки 72, Дніпро, Україна, 49010
[2] Інститут технічної механіки НАН України та Державного космічного агентства України
вул. Лешко-Попеля 15, Дніпро, Україна, 49005

Розглянуто проблему шкідливих резонансних коливань тиску в твердопаливних прискорювачах на початковому етапі розгону космічної системи «Аріан-5». Зроблено припущення щодо пов'язаності цих коливань зі змінами геометричних характеристик прискорювачів Р230 у результаті формування в них порожнин, заповнених продуктами згоряння твердого ракетного палива. Розраховано об'єми порожнин, що утворюються під час вигоряння палива. Розглянуто схему двигуна, що виникла після вигоряння першої частини заряду. Вочевидь, форму порожнини можна апроксимувати моделлю резонатора Гельмгольца. Також враховано, що у появі пульсацій тиску в камері згоряння ракетного двигуна відіграє роль поступове прогрівання верхніх шарів твердого палива і пов'язані з цим зміни хвильового опору палива. Звідси виникають резонансні явища у порожнинах, що формуються. У результаті розгляду різних резонаторних систем для опису фізичної моделі резонансних явищ обрано модель резонатора Гельмгольца, що найбільше підходить до розрахункового пояснення пульсацій тиску. При розрахунках за цією моделлю одержано ту саму частоту, що й у результатах вимірювань під час льотної експлуатації космічної системи «Аріан-5». Запропоновано напрямок вирішення проблеми зменшення резонансних коливань у камері згоряння.

Ключові слова: тиск, сопло, хвильовий опір, пульсації, резонанс, частота.