On the possibility of some Pogo options implementation in the light of Starship program's problems

Yu. I. Lobanovsky

Summary

This paper provides some estimates of the value of differences in the excitation of hydroacoustic oscillations in the engines supply lines with fuel and oxidizer, which show that the connection between pressure and thrust oscillations is stronger in the oxidizer supply lines. Therefore, a dangerous self-oscillatory process of Pogo-type is more likely on them, and speed of its development in this case, other things being equal, should be higher, which is confirmed by the launches of Starship's IFT-1 and IFT-2. However, examples of the occurrence of Pogo with hydroacoustic oscillations in the fuel supply lines of engines have also been found.

It has been shown that pressure growing in combustion chambers of liquid-propellant rocket engines increases the rate of Pogo development and, therefore, degree of danger of this self-oscillatory process, and analysis of data regarding Angara rocket clearly demonstrated the possibility of Pogo excitation in rocket systems with closed-cycle engines.

The reasons for the first disappearance of Pogo from the attention of rocket engineers in recent decades, and then for its unexpected return are described. They were caused solely by changes in designs of modern rockets and their engines. From the presented materials it follows that Starship is practically an "ideal Pogo habitat", and also that in order to successfully complete the creation of this space system, a special program is needed to assess possible manifestations of Pogo and to combat all variants of this very dangerous process even before they occur implementation.

Keywords: *Pogo, self-oscillations, crash, Starship, frequency, excitation, hydroacoustic oscillations, own oscillations*

Symbol list

c – speed of sound
e^* – specific heat of combustion of fuel
e_{st} – stoichiometric specific heat of combustion
F – engine thrust
f_e – own frequency of rocket hull
f_n – frequency of hydroacoustic oscillations
g – acceleration of free fall
L – length
L_{eq} – equivalent length of oscillatory circuit
N – jet power
p – pressure
S – cross-sectional area
u – characteristic velocity of the jet (specific impulse)
v – fluid flow speed
α – oxidizer excess coefficient
μ – mass flow rate of liquid flow
ρ – liquid density
θ – ratio of masses of oxidizer and fuel
ε – relative magnitude of disturbance
Δ – difference symbol

Index

0 – unperturbed value

I. Introduction

Paper [1] described a method for calculating the frequency of oscillations in flow-through hydroacoustic oscillatory circuits corresponding to supply lines with propellant components of liquid-propellant rocket engines, with internal elements introducing energy into the liquid flow. In it, and in the subsequent series of works [2 – 4], this method was used to assess the possibility of excitation of Pogo-type self-oscillations, that provided an explanation for all incidents with explosions of Starship, which were in its first [1] and in the second flights [2 – 4]. As is known, processes such as Pogo in the past also led to serious problems during rocket launches, and often ended in their accidents and explosions [5].

For reasons that are described later in this work, the severity of the problems associated with Pogo in recent decades – during the stagnation of rocketry, has sharply weakened. But very recently, when a generation of rocket engineers had already grown up, for whom the word "Pogo" meant either little or nothing at all, this formidable process suddenly returned. We argue that all the main problems of Starship, as well as he Angara-A5 rocket, are associated with its various manifestations.

Now all this seems quite obvious, but we still don't know not only the frequency spectra of hydroacoustic oscillations in the fuel lines of Starship rocket or the elastic vibrations of its body, and their meanings, but even any mention of the fact that any vibrations occurred during two its flights. Obviously, this is the policy of SpaceX, the developer of this reusable rocket system, which has become noticeably stricter around mid-December 2023. At the same time, the conditions for Pogo-type processes implementation during its flight, in some cases, had never been encountered previously during the launches of disposable rockets, which usually used open-cycle engines, in contrast to modern closed-cycle rocket engines.

Therefore, here we describe a more in-depth analysis of the physical foundations of hydroacoustic self-oscillations excitation, as part of a complete theory of Pogo, and also provides information on the recorded and made available to the public Pogo type oscillations on a modern rocket with a closed cycle engine.

II. Estimation in the ratio of disturbances during excitation of hydroacoustic oscillations in the fuel and oxidizer supply lines

One of the necessary conditions for excitation of Pogo is the existence of a positive feedback between hydroacoustic and elastic oscillations. Without trying to fully describe it now, we will limit ourselves to only considering the question of the influence of hydroacoustic disturbances on what causes elastic vibrations, that is, on oscillation of the rocket power plant thrust. This aspect of a complex process is now of greatest practical interest due to the fact that, as a rule, hydroacoustic disturbances initiating Pogo arose in the oxidizer line; at least, all cases known to us when liquid oxygen was used as an oxidizer occurred exactly this way. And the first process of the occurrence of Pogo during the flight of Starship is explained by us through hydroacoustic disturbances in the methane line, that is, fuel [1]. At the same time, the fuel in all known big rocket engines was always supplied to the main combustion chamber in excess, and the oxidizer, accordingly, with a deficiency, in relation to the stoichiometric ratio of these propulsion components, because the fuel always turned out to be a lighter component, and, as a result, the maximum effective velocity of the jet was achieved precisely with this ratio of components, see, for example, [6].

This means that a change in the flow of fuel and oxidizer into the main combustion chamber due to fluctuations in the flow rate of one of these components leads to different consequences. If a fluctuation occurs in the fuel line, then the thrust changes only due to a change in the flow rate of the working fluid. If a fluctuation occurs in the oxidizer line, then the thrust changes both due to a change in the flow rate of the working fluid and due to a change in the thermal energy released at that moment in the main combustion chamber of the rocket engine. At the same time, the same change in the flow rate of the working fluid due to fluctuations of the oxidizer (heavy component) affects the engine thrust less than the fluctuation of the fuel (light component). Let's try to bring these effects together and quantify them.

First, let's present 3 formulas that describe the main characteristics of a rocket engine: μ is the flow rate of the working fluid through it, F is its thrust and N is its power (the power of its jet stream). As is known, the mass flow rate of liquid μ in a pipe is determined as follows:

$$\mu = \rho v S, \qquad (1)$$

where ρ is the density of the liquid, v is the speed of its flow in the pipe, S is the cross-sectional area of the pipe. Engine thrust F is found from the formula:

$$F = \mu u, \qquad (2)$$

where μ is the flow rate of the working fluid, u is the characteristic velocity of the jet stream (specific impulse). In this case, the power of the jet stream is equal to:

$$N = \frac{\mu u^2}{2} \qquad (3)$$

In addition, the thermal power of the rocket engine is important to us. It, accurate to small corrections, is determined by parameter e^* – specific heat of propellant combustion, as well as deviation degree of the combustion process from stoichiometry, characterized by two values dependent on each other: α –oxidizer excess coefficient (which in practice is always less than 1, that is a formal excess is actually a disadvantage), or the parameter θ – ratio of the masses of the oxidizer and fuel. Then

$$e^* = \frac{\alpha e_{st}}{1+\theta}, \tag{4}$$

where e_{st} is the stoichiometric specific heat of combustion (see [6]).

If, as a first approximation, we neglect the influence of the nozzle geometry on the effective exhaust velocity, that is, changes in the efficiency of the process from the ratio of the cross-sectional area of the nozzle at the exit to the area of its critical section, then for the first estimates we can assume that

$$N \sim e^*, \tag{5}$$

besides, now we will only be interested in comparing the characteristics of two supply lines of the same engine, and in this case relation (5) is accurate.

The main parameter characterizing hydroacoustic oscillations is usually magnitude of pressure disturbances p in fuel line behind pump, since they are the easiest to measure and they are greatest there. And in the previous formulas, the main dynamic parameter of the fluid was its flow velocity v. Therefore, we need to relate the oscillations of speed and pressure, for which we use the Bernoulli equation. Since the change in the height of the section of the supply line behind the pump is always small, we use the Bernoulli equation without hydrostatic component:

$$p + \frac{\rho v^2}{2} = \text{const} \tag{6}$$

Then, if we accept the following notation: index 0 refers to the undisturbed parameter, Δ is the symbol of the difference, ε is the relative magnitude of the disturbance, then for the pressure behind the pump we obtain the following expressions:

$$p = p_0 \pm \Delta p = p_0 (1 \pm \varepsilon),$$

$$\Delta p = \varepsilon p_0,$$

and from equation (6) we get

$$v = v_0 \pm \Delta v = v_0 \left[1 \pm \left(\frac{p_0}{\rho v^2}\right)\varepsilon\right],$$

and from relations (1, 2)

$$\mu = \mu_0 \left[1 \pm \left(\frac{p_0}{\rho v^2}\right)\varepsilon\right]$$

Let us now consider the excitation of a disturbance in the flow of fuel, which enters the main combustion chamber in excess. In this case, the energy release during combustion will not change, and N = const. Then from relation (3) it follows:

$$\left(\frac{\Delta F}{F_0}\right)_f \approx \frac{1}{2}\left(\frac{p_0}{\rho v^2}\right)\varepsilon \tag{7}$$

If a disturbance is excited in the oxidizer flow entering the main combustion chamber when there is a deficiency, then the energy release during the combustion process will increase, and from relations (3 – 5) it follows that:

$$\left(\frac{\Delta F}{F_0}\right)_{ox} \approx \frac{\theta_0 + 1.5}{\theta_0 + 1} \cdot \left(\frac{p_0}{\rho v^2}\right)\varepsilon \tag{8}$$

Dividing the magnitude of the thrust disturbance during oscillations in the oxidizer line (8) by its magnitude during oscillations in the fuel line (9) and assuming that the fluid flow velocities there are close, we obtain the relation

$$\frac{\Delta F_{ox}}{\Delta F_f} \approx \frac{p_{ox}\rho_f}{p_f \rho_{ox}} \cdot \frac{2\theta_0 + 3}{\theta_0 + 1} \cdot \theta_0, \tag{9}$$

from which one can evaluate "sensitivity" of the engine by its thrust to pressure fluctuations behind the fuel and oxidizer pumps.

From formula (9), in particular, it follows that in the case of Raptor-2 engine (see [1]), pressure oscillations in the oxygen supply line lead to thrust disturbances approximately 2.2 times greater than disturbances in the methane line. Further, thrust disturbances cause new flow oscillations both at the entrance to the pump and at the outlet from it, and in the process, with a general disturbance amplification factor of more than 1, positive feedback arises, which is necessary to excite Pogo. From the estimates obtained, it follows that Pogo, when supported by this process by disturbances in the oxygen flow, should be excited more easily and quickly. Indeed, in the first flight of Starship, when Pogo process occurred during oscillations of the methane flow, the control system was able to temporarily suppress it, while creating a 2 orders of magnitude slower oscillatory process in the form of superspikes that occurred every 12 seconds [1]. And in both cases of Pogo manifestations in the second flight during oscillations of oxygen flows, the control system didn't have time to do anything, and both times, both in the first and in the second stages, explosions occurred [3, 4].

It should be noted that so far only one case of Pogo excitation with oscillations in the fuel line has been known. In Titan II GLV rocket, which was a variant of combat rocket designed to launch manned Gemini spacecraft, undamped Pogo oscillations were detected, which created vibration accelerations of a magnitude completely unacceptable for astronauts, although the rocket, before the start of work on suppression of Pogo, had never entered the modes of engine shutdown and/or destruction in flight. It was possible to come to a similar result only when they began to try to prevent Pogo. This was the first time that American rocket developers had encountered such manifestations of Pogo that they had to eliminate them. NASA and the US Air Force have formed a special committee to study rocket vibrations. Battle against Pogo lasted 22 months – from March 1962 to January 1964, no less than 24 launches of Titan II rockets were carried out, until they achieved the desired result – reducing level of maximum vibrations to ± 0.25 g. This problem was solved by increasing the pressure in the fuel tanks and installing two different types of hydroacoustic oscillation suppressors in oxidizer (nitrogen tetroxide) and fuel (aerozine 50) lines. It is interesting to note that when an initial attempt was made to suppress pressure oscillations in the oxidizer line alone, "instead of damping the Pogo effect, the vibrations at the payload actually increased to ± 5 g's, forcing an early first stage engine shut down and mission loss" [7]. Estimate (9) shows that pressure oscillations in the nitrogen tetroxide line led in the LR-79 engine (see [8]) to thrust disturbances approximately 1.6 times greater than in the aerozine 50 line.

In principle, this ratio isn't very different from what was obtained for Starship, so this result once again confirms the reality of self-oscillations of Pogo type in the first flight of Starship.

In addition, from the above estimates one can see no less than a proportional relationship between thrust disturbances and the pressure of the fuel component behind the pump. This should lead to the fact that the higher the pressure in the rocket engine, the faster Pogo process develops and becomes more and more intense, if it has occurred, that is, the potential danger of Pogo grows with increasing pressure in the engines. Indeed, in Saturn V rocket, such self-oscillations occurred at least twice, but once only several panels were torn off, and in the second, one of the five second-stage engines shut down prematurely, but there were no catastrophic consequences [5, 7]. At the same time, on Starship rocket, the pressure behind the pumps in Raptor-2 engines is several times higher than that in F-1/J-2 engines of Saturn V, and all 3 Pogo processes that arose in two flights ended in explosions. That is, the more advanced the engine, the more dangerous the development of Pogo in a rocket system with such engines.

III. Analysis of Pogo process that arose on a Russian rocket with closed-cycle engines

Another objection to the idea that the main cause of explosions of Starship system with closed-cycle engines is self-oscillation of Pogo could be that all rockets in which Pogo processes previously occurred (Saturn V, Atlas, Titan II, UR-100), were driven by open-cycle liquid rocket engines, and the first rocket that died due to Pogo, a three-stage version of R-7, even used an external drive for fuel pumps from a turbine operating on hydrogen peroxide decomposition products [5, 7] At the same time, the analysis doesn't show any significant influence of the "openness" or "closeness" of the rocket engine cycle on the possibility of the occurrence of Pogo, but the criterion of truth is practice. You can, of course, recall that the case of the occurrence of Pogo in the fourth test flight of Soviet lunar rocket N1 with closed-cycle NK-15 engines still seemed to be, but due to a lack of information this has not become a generally accepted fact [5, 9]. So, to analyze the case of Pogo occurrence on a modern, just-finished rocket with closed-cycle engines, in which the frequency of the process is known, would be very useful for improving the understanding of what happened with Starship system.

And such a case presented itself to us. Angara-A5 – a new Russian heavy-class launch vehicle has a package design – the central module (second stage) is surrounded by 4 almost similar side modules, which together form the first stage. In this case, the engines of the first and second stages are launched on the ground almost simultaneously, and in order for the second stage to fulfill its role, that is, to work after the side modules separate, its engine, the same as on the side modules, needs to be throttle, up to 30 % of the nominal value [10]. Stand tests have shown that RD-191 engine used there is capable of operating quite efficiently and stably across this entire thrust range [11]. However, more than 4 years after the first test launch of Angara-A5 in December 2014, officially qualified as "successful" [12], in January 2019, P. S. Levochkin, chief designer of NPO Energomash, developer and manufacturer of RD-170/171, RD-180 and RD-191 engine family, unexpectedly stated that "in the process of creating RD-191 engine, a problem was discovered in ensuring stable operation in deep throttling modes of thrust (below 38 % of the nominal value". In such a situation, low-frequency vibrations begin in the engines, which ultimately "can lead to resonance and destruction of the launch vehicle structure" [13, 14].

It is now unknown whether this speech by the chief designer took place at Korolev's readings or not (author wasn't present at the 2019 readings), since "the existence of such a defect was rejected by head of Roscosmos Dmitry Rogozin on the same day. He called that the data about problems with RD-191 engine for Angara-5 heavy rocket is surprising and absurd" [15]. However, the end result of all this tragicomedy around Angara-5A for us was public access to information, which was reported by P. S. Levochkin: "This problem manifests itself in the occurrence of low-frequency (LF) oscillations of engine thrust (about 4 Hz) when switching to mode 38 % of the nominal thrust value and below" [14].

After this, having an image of the universal module of Angara-A5 rocket against the background of a metric ruler [16], see Fig. 1, it is easy to estimate the height of kerosene tank of this module – about 7.4 m. By adding the typical length of the oxygen pipeline from the bottom of the kerosene tank to the engine – 3.0 m [1], we determine the length of the oxygen supply line section from the tank to the pump as 10.4 m ($L_2 \approx 10.4$ m).

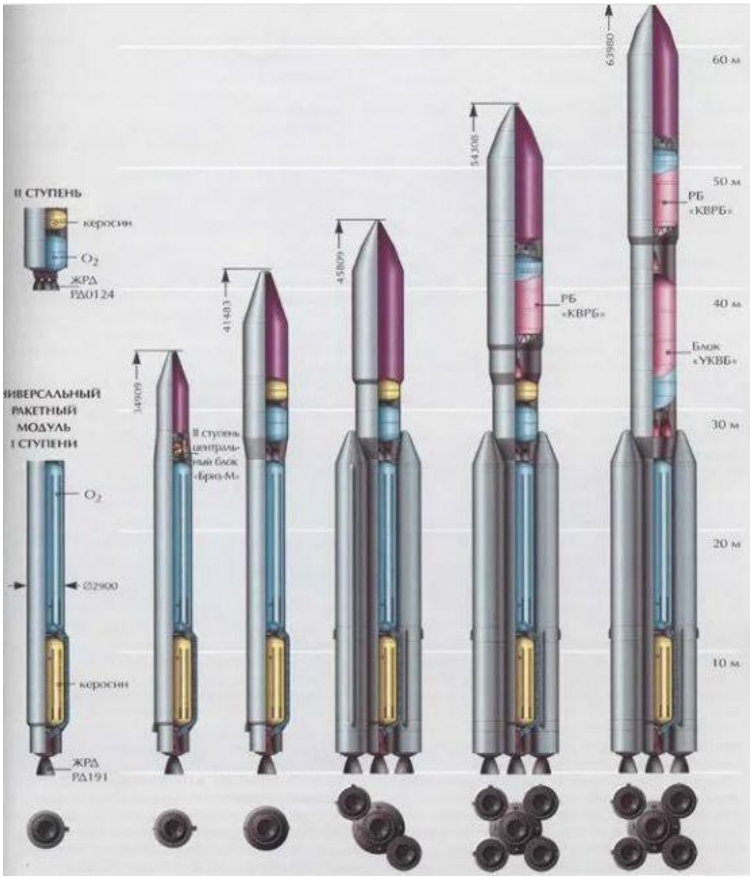

Fig. 1 – Universal module and various variants of Angara rocket [16]

According to the image of RD-191 engine from source [11], Fig. 2, you can also estimate the length of the oxygen supply line section from the pump to the gas generator in the range of 1.5 – 2 m – see the intricately curved channel with black dots along the entire length (L_1 = 1.5 – 2 m, using the fact that the cut diameter of engine nozzle is 1.43 m [17]).

Fig. 2 – RD-191 engine

The pressure behind pump of RD-191 isn't known exactly, but the pressure in its main combustion chamber is known – 25.8 MPa. The pressure behind the pump of its progenitor, RD-170/171 engine, is also known – 60.2 MPa, as well as the pressure in each of its four combustion chambers – 24.5 MPa [18]. From recalculating these data, with a good degree of accuracy the pressure behind RD-191 pump is easily obtained – p_2 = 63.4 MPa, which is only 10 % less than that of Raptor-2 engine. The pressure at the inlet to RD-191 pump is also unknown, but it is clearly in the range p_1 = 0.3 – 0.4 MPa (the first value is typical for rockets of the 60s – 70s, for example, for Saturn V lunar rocket using aluminum alloys, and the second – for Starship system with a stainless steel hull). Information that RD-170/171/191 engines have booster pumps that prevent the occurrence of cavitation on the main pumps [18], which Raptor-2 engine doesn't have, also indicates that the most likely option is with a lower pressure at entrance to RD-191 pump group, however, we will still calculate the frequencies of hydroacoustic oscillations for both possible pressure values at the pump inlet. The known frequency of these oscillations, about 4 Hz, closes the complex of data and allows them to be verified.

Then the pressure drop across the oxygen pump group of RD-191 engine at the nominal operating mode is p_2/p_1 = 210 with the most probable value p_2 = 0.3 MPa, which is greater than that of the oxygen pump of Raptor-2 engine and is close to the pressure drop across the methane pump of the latter. At p_2 = 0.4 MPa at the nominal mode, p_2/p_1 = 158.5 Throttling to 38 % of the thrust is estimated to correspond to a reduction in the pressure in the combustion chamber to approximately 41 % of the nominal [6]. Therefore, the pressure drop in this mode is reduced to $p_2/p_1 \approx 85/65$. Using these data, calculations were made of the frequencies of hydroacoustic oscillations in the oxygen supply line of RD-191 engine. The length of the intricately curved path between the outlet of the pump and the entrance to combustion zone of gas generator was determined by calculation from the condition that in the throttle mode the oscillation frequency is f_n = 4.00 Hz. And then the nominal operating mode of the engine was calculated, in which the engines of the side blocks of the Angara-A5 rocket operated, and with the length of the L_1 path determined from the first calculation, the frequency of hydroacoustic oscillations was calculated at the nominal operating mode of the engine, see Table 1.

It uses the following notations: c – speed of sound in liquid cryogenic oxygen, p_2/p_1 – degree of pressure increase in the oxygen pump of RD-191 engine, L_1 – length of the oxygen path from the pump to the gas generator, L_2 – length of the oxygen path from the tank to the pump, L_3 is their sum, L_{eq} is the effective length of the oscillatory circuit, that is, the length that corresponds to the frequency of oscillations that occur in it in the absence of a pump, f_n is the frequency of hydroacoustic oscillations of liquid oxygen in the path.

Table 1

Rocket Stage Engine	p_2/p_1	L_1 (m)	L_2 (m)	L_3 (v)	L_{eq} (m)	f_n (Hz)
c = 930 m/s						
Angara-A5 Universal module RD-191	210	1.51	3.0 + 7.4	11.91	90.7	2.56
	85				58.2	4.00
	158.5	1.97		12.37	90.0	2.58
	65				58.1	4.00

It can be seen that the lengths of the curved channel from the oxygen pump to the gas generator L_1 obtained in these calculations completely coincided with the preliminary estimates "by eye" from Fig. 2 (1.5 – 2 m), which allows us to assert that the results presented in Table 1 quantitatively correspond well to the real data. In this case, the frequency of oscillations in the oxygen supply line of the rocket at the nominal operating mode of the engine changes little from the options possible in implementation and amounts to 2.55 – 2.6 Hz.

Estimates of the own frequency of a rocket structure elastic vibrations without side modules f_e using the method described in [1, 2] lead to the value $f_e \approx 12$ Hz, which is very close to the data for Titan II rocket, which, of course, was to be expected, since that rocket 60s and this universal module are very similar in design, size and mass, only the fuel in it is different. However, as part of Angara-5 structure, this module is closely surrounded by four modules approximately the same as it, which naturally should greatly influence the own frequencies of their elastic vibrations. And they can no longer be assessed in the simplest way indicated above. But, from the experimental data it follows that if at a hydroacoustic frequency of 4 Hz we have a strong response from the hull of the central block, then the frequency of its elastic vibrations in Angara-A5 version should be close to either 4 Hz or 8 Hz.

And Angara-1.2, with approximately the same natural frequency that was obtained in an approximate estimate – 12 Hz, and with the nominal thrust of the first stage engine with a hydroacoustic frequency of 2.55 – 2.6 Hz, doesn’t experience any Pogo. In the worst case, one could look for a multiplicity of 5 between hydroacoustic and elastic frequencies, but practice has shown that such multiplicities are no longer capable of any excitation, even if they correspond to precise frequency matching.

As a result, we see that on the modern Angara-A5 rocket with RD-191 closed-cycle engine, a completely classic "Pogo process" has clearly been identified, which completely removes doubts about the possibility of a similar process occurring during flights of Starship.

IV. The reasons why modern rocket engineers weren’t ready for the return of Pogo

By the turn of the 50s – 60s of the XX century, at the time of humanity’s entry into space, rocket engineers for the first time really encountered Pogo – continuous or, worse, rapidly growing oscillations of the rocket structure and the associated powerful pressure oscillations in supply lines of engines. The first such case ended with the death of two three-stage "lunar" exemplars of Soviet R-7 rocket in the fall of 1958 [5]. The term Pogo itself arose in the United States in 1962, during a long, exhausting almost two-year battle of Martin Company, NASA and the US Air Force for the opportunity to install a Gemini manned spacecraft on Titan II combat rocket. That generation was very persistent, and after 24 launches of Titan II, they achieved their goal.

Gradually, various methods of suppressing Pogo were empirically developed [5, 7]. "Since that time NASA has had a strict "no Pogo" philosophy that was applied to the development of the Space Shuttle." – see [7]. Adhering to the "no Pogo" philosophy in recent decades – during times of stagnation in rocketry – was also helped by the fact that the designs of rockets, and therefore the own frequencies of their elastic oscillations, changed little, and the liquid rocket engines on first stages with open-cycle, were replaced either by closed-cycle liquid-propellant rocket engines or solid-fuel boosters. And the closed cycle made it possible to increase the pressure in the main combustion chamber of the liquid-propellant rocket engine by 2 – 4 times, and required an even more significant increase degree of pressure difference on at least one, or even both, pumps. Since, all other things being equal, the frequency of hydroacoustic oscillations is approximately inversely proportional to the square root of this difference [1], it decrease significantly and went out of resonance with the frequencies of elastic vibrations of the rocket hulls – therefore, Pogo disappeared by itself without any special efforts.

And it was practically forgotten when it unexpectedly returned from oblivion. In Russia and in the USA this was caused by different reasons. The package design of Angara-5A rocket required strong and prolonged throttling of RD-191 closed-cycle engine, such that its characteristics practically returned to the level of those of open-cycle engines. And along with this, Pogo also returned, which the creators of Angara didn't even think about. And for them, self-oscillations in two oscillatory circuits interconnected by positive feedback became "dangerous engine vibrations". It is quite clear what they can achieve with such an understanding of this phenomenon.

The return of Pogo during the first flights of Starship system was caused by a more complex set of reasons. Firstly, the enormous size and starting mass of this system naturally compensated for the increase in the frequencies of own elastic vibrations caused by the use of stainless steel as a structural material. And if its first and second stages form a single oscillatory circuit, not separated by an insert with sharply different characteristics (as during IFT-1), then the own frequency of hull oscillations of this rocket system is close to the corresponding parameter of Saturn V rocket. Secondly, the influence of a record high pressure in the main combustion chamber of Raptor-2 to the hydroacoustic frequency in the oxygen line was compensated by the extremely dense layout of this engine, which made it possible to greatly reduce the length L_1 of the most important section of the hydroacoustic oscillatory circuit – the pipeline between the pump and the oxidation gas generator. The first factor reduced the frequency, and the second increased it. In addition, moving the oxygen tank down the hull closer to the engines greatly reduced the length L_2 of the oscillatory circuit second section – the pipeline from the tank to the pump, which also increased this frequency. As a result, both elastic and hydroacoustic frequencies turned out to be quite moderate and were of the same order, which contributed to different resonances. As an illustration, we can recall that in the oxygen supply lines, for the reasons stated above, the hydroacoustic frequency in Super Heavy stage was quite high – about 10 Hz, and in the universal module of Angara rocket, which was one and a half orders of magnitude smaller, it was about 2.5 Hz. The main reason is that Raptor-2 has a parameter $L_1 \approx 0.4$ m, and RD-191 – $L_1 \geq 1.5$ m. And only strong throttling of RD-191 raises this frequency and brings it into the "resonance zone" of the universal Angara module. And in the methane supply line of the first stage of Starship system – Super Heavy, where both factors reducing the length of the oscillatory circuit are absent, the hydroacoustic frequency dropped so much (~ 2 Hz) that Pogo excitation conditions arose already at a multiplicity of frequencies of 2 or 3.

In general, it can be noted that Starship is almost an "ideal Pogo habitat", since the complexity of the missions performed by this system creates a huge variety of factors that greatly change the hydroacoustic and elastic frequencies of the system as a whole and its individual stages depending on the flight phase. The following changes significantly: mass of objects, degree of engines throttling that capable of operating in a record wide range of pressures and thrusts, pressure in tanks due to large fluctuations in hydrostatic pressure and the release of boosting gases, which leads to strong changes in pressure at the inlet to the pumps, and also, possibly, sometimes to the appearance of cavitation on the main pumps in the absence of booster pumps, which can greatly change the speed of sound in the medium, and therefore the frequency of the process. And on top of all this are frequency multiplicities, as well as the significant design changes being considered. Essentially, it is already obvious that without a program for analyzing possible manifestations of Pogo and combating all emerging variants of this very dangerous process, the creation of Starship rocket and space system cannot be successfully completed.

Conclusions

1. The assessments of differences magnitude in the excitation of hydroacoustic oscillations in the engine supply lines with fuel and oxidizer show that the connection between pressure and thrust oscillations is stronger in the oxidizer supply lines. Therefore, Pogo is more likely will arose on oxidizer supply lines , and the speed of its development in this case, other things being equal, should be higher, which is confirmed by the launches of IFT-1 and IFT-2 of Starship.
2. However, examples of the occurrence of Pogo with hydroacoustic oscillations in the fuel supply lines of engines have also been found.
3. Increasing the pressure in the combustion chambers of liquid rocket engines increases the rate of Pogo development and, therefore, the degree of danger of this self-oscillating process.
4. Analysis of data relating to Angara rocket clearly demonstrated the possibility of Pogo excitation in rocket systems with closed cycle engines.
5. The reasons for the first disappearance of Pogo from the horizon of attention of rocket engineers, and then for its unexpected return, are caused solely by changes in the design of modern rockets and their engines.
6. Starship system is practically the "ideal Pogo habitat". To successfully complete the creation of this space system, a special program is needed to assess possible manifestations of Pogo and combat all variants of this very dangerous process even before their emergence.

Literature

1. Yu. I. Lobanovsky – Cause of Starship crash on first flight. *Synerjetics Group*, 05.10.2023, 19 p. // https://www.synerjetics.ru/article/starship_crash_eng.pdf
2. Yu. I. Lobanovsky – Causes of Starship both stages crashes on second flight. *Synerjetics Group*, 04.12. 2023, 10 p. // https://www.synerjetics.ru/article/second_flight_eng.pdf
3. Yu. I. Lobanovsky – Mechanism of Starship first stage explosion during its return maneuver. *Synerjetics Group*, 12.01.2024, 7 p. // https://www.synerjetics.ru/article/boostback_eng.pdf
4. Yu. I. Lobanovsky – Explosion mechanism of Starship second stage during second flight at the end of its acceleration. *Synerjetics Group*, 18.01.2024, 7 p. // https://www.synerjetics.ru/article/second_stage_eng.pdf
5. B. I. Rabinovich – Instability of liquid-propellant rockets and space vehicles and some fragments of the history of combating it. *Preprint IKI RAS*, 2006, 40 p. // http://www.iki.rssi.ru/books/2006rabinovich.pdf (in Russian)
6. Yu. I. Lobanovsky – Conservation laws and phenomenology of rocket engines. *Synerjetics Group*, 30.06.2008, 21 p. // http://www.synerjetics.ru/article/rocket_engines.pdf (in Russian)
7. C. E. Larsen – NASA Experience with Pogo in Human Spaceflight Vehicles. *NTRS – NASA Technical Reports Server*, NATO-OTAN-RTO-MP-AVT-152, 10 May 10 2017, 23 p. // https://ntrs.nasa.gov/api/citations/20080018689/downloads/20080018689.pdf
8. Anon. –Turbopump Systems for Liquid Rocket Engines. NASA SP-8107, 1 August 1974 // https://ntrs.nasa.gov/citations/19750012398
9. I. Afanasiev – N-1: Top secret. Wings of Motherland, no 9 – 11, 1993 // https://epizodyspace.ru/bibl/k-r/1993/9-n-1.html (in Russian)
10. Angara-A5. *Wikipedia* // https://ru.wikipedia.org/wiki/Ангара-А5 (in Russian)
11. RD-191. *Wikipedia* // https://ru.wikipedia.org/wiki/РД-191 (in Russian)
12. List of Angara space rocket launches. *Wikipedia* (in Russian)
13. The developer reported a problem with the engines of the Angara rocket. *RBK*, 18.01.2019 // https://www.rbc.ru/technology_and_media/18/01/2019/5c41528b9a79471c32f1370e (in Russian)
14. P. S. Levochkin, E. N. Semina, I. V. Burtsev – Ensuring stable operation of a liquid-propellant rocket engine in deep throttling modes. XLIII Academic Readings on Cosmonautics, Section 3, .29.01 – 01.02.2019, p. 72 – 73. (in Russian)
15. The engines of Angara rocket were called into question. *BC, News, Omsk*,17.03.2019 // https://bk55.ru/news/article/146809/?utm_source=google.com&utm_medium=organic&utm_campaign=google.com&utm_referrer=google.com (in Russian)
16. Angara rocket family // https://i1.wp.com/oruzhie.info/images/stories/angara/raketa-nositel-angara-06.jpg
17. V. P. Zyuzlikov et al. – Gas-dynamic processes in gas duct of shallow-depth launch complex for light-class space rockets. *Science City Research*, **1**, 4 (22), October – December, 2017, p. 14 – 22// http://www.journal-niss.ru/journal/archive/22/journal_22.pdf (in Russian)
18. LRE RD-170 (11D521) and RD-171 (11D520). *Liquid Propellant Rocket Engines* // http://www.lpre.de/energomash/RD-170/index.htm (in Russian)

Moscow,
08.02.2024

Yu. I. Lobanovsky