Starship Program: Results 2023

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A time to throw stones and a time to gather stones; A time to embrace and a time to shun embracing.
Ecclesiastes 3:5

Summary

This work briefly describes main events of 2023 in Starship program, assesses general state of affairs, shows previously unprecedented importance of Pogo-type self-oscillation analysis for success of this rocket system development, and also points out mistakes of SpaceX senior management during the implementation of this program.

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

I. Main technical results for 2023

During 2023, in Starship program, 4 static fire tests of Starship first stage (Super Heavy booster) power plant were carried out in full, as well as 2 flights (see [1 – 3]). Ground tests were carried out with only the first stage, and both flights took place with a fully equipped two-stage system. The author chose number of engines that failed during the tests as a generalized characteristic of these tests results, since it is indicator that is associated with the processes that now determine success or failure of the test. As you know, there were 33 Raptor-2 engines on the first stage (Super Heavy), and 6 on the second stage (Ship).

These data are presented in Table 1, using the following notation:

A is number of engines that didn't turn on at the start;
B is number of engines stopped during ground test or in flight;
C is of them that may not have switched off completely;
Σ is the total number of engines that didn't operate for the entire planned time due to internal reasons.

In the second flight (test No. 5), the operating time of B9 booster is divided into 2 parts: the first – acceleration of Starship (173 s) and the second – braking and turning maneuvers of booster (from restarting the inner ring engines to explosion – 27 s). At the same time, 3 central engines didn't stop working from the start.

Second stage flight, which was quite successful for a long time, ended with an unexpected and instant shutdown of telemetry, so that it was impossible to determine from it the causes of this incident. But it is quite obvious that it was explosion of its engines [3]. How many of them exploded? Since there were two groups of 3 engines each – standard Raptor-2 engines and Raptor-2 engines with a vacuum nozzle, also slightly different in location relative to oxygen tank, it is reasonable to assume that, most likely, 3 engines from that group exploded, which was less resistant to the explosive process. A more accurate conclusion can be made if the exact drawings of the second stage power plant are known.

Table 1

N	Data	SH/Ship	Event	Duration (s)	A	B	C	Σ
1	02/09/2023	B7	Test	~ 6	1	1	0	2
2	04/20/2023	B7	Flight	~ 100/145	3	5	2	8
3	08/07/2023	B9	Test	2.7	0	4	0	4
4	08/25/2023	B9	Test	~ 6	0	2	0	2
5	11/18/2023	B9	Flight	173/27	0/1	0/9	0/0	0/13
		S25		322	0	3?	0	3?
6	12/29/2023	B10	Test [10]	~ 10	–	–	–	–

During the first flight, all engines shutdowns occurred approximately at the 100th second of flight; after the 145th second, when the rocket began to perform off-design maneuvers such as a "dead loop", it apparently became completely impossible to assess the condition of the engines. At the same time, second stage engines didn't start in the first flight. In static winter – autumn fire tests, from 1 to 4 engines were lost in 3 – 6 seconds, and their number even increased from February to August. The engine shutdown before launch was apparently caused either by the consequences of previous fire tests, including those with a smaller number of engines, or by accidental reasons.

In the second flight, all engines of the first stage worked in the acceleration section of the trajectory with virtually no problems, except for one nuance, which will be discussed separately later. The same can be said about the operation of the second stage engines, with the exception of the very final section of its acceleration trajectory. As a summary, based on the analysis presented in [3], we can say that in this flight absolutely all 39 Starship engines showed quite reliable operation in the conditions for which they were designed, which, of course, is a great achievement of SpaceX company. Problems with the engines began only when they found themselves in conditions not foreseen by their developers, and in which no rocket engine is capable of operating normally. These conditions arose 3 times during the flight, and in the first case, Starship "slipped" through the dangerous mode due to its brevity, and the next 2 ended with two explosions of successfully separated stages. The analysis showed that the cause of the accident in the first flight, as well as all three dangerous modes in the second, was the occurrence of Pogo-type oscillations, but an analysis of all the nuances of these processes, which can be found in papers [1, 3], isn't within the scope of this work. Here we only briefly name common causes and describe SpaceX efforts to identify and eliminate them.

At the very end of 2023, the fourth static test was carried out. For the first time, the number of engines that stopped during this test is not reported. Therefore, in Table 1 in the last line there are dashes only. And, apparently, SpaceX transparency policy has changed dramatically since mid-December 2023. However, the author may write in a separate work why this happened.

II. General state of affairs in Starship program by the end of 2023

It seems to us that we can briefly describe the state of affairs in Starship program by the end of 2023 as follows:

1. The most important obstacle on the path to success of Starship first test flight (IFT-1) and, at the same time, its most important result, was the self-oscillating process of Pogo-type during acceleration of the system in the form of two stages assembly. Hydroacoustic disturbances in methane supply lines to the first stage engines and the rocket hull own elastic vibrations caused a Pogo process, the struggle of Starship smart control system with which led to low-frequency oscillations of this system with so-called superspikes, repeating every 12 seconds. This ultimately led to crash of Starship during its maiden flight.

2. SpaceX realized this no later than the beginning of June and during June-August took measures to prevent the occurrence of the process described above by creating and integrating into Starship the so-called interstage hot separation compartment (FHSI). This compartment, due to its rigidity, significantly exceeding the rigidity of both Starship stages, divided the single oscillatory circuit of the assembly into 2 parts, noticeably changing own frequencies of the system, eliminated positive feedback between two types of oscillations, and, thus, didn't allow this Pogo process to arise. At the same time, the FHSI compartment made it possible to perform hot separation of stages, and, in principle, increase payload of the system due to a decrease in gravitational losses.

3. For unclear reasons, SpaceX decided to hide the appearance of Pogo on Starship during the first flight IFT-1, and presented measures to suppress Pogo solely as actions aimed at increasing the payload. And in this way Pogo was eliminated.

4. However, unexpectedly, in the second test flight or IFT-2, three Pogo processes appeared at once instead of one. And it was no longer possible to eliminate them in the previous way. Despite the undoubted success of IFT-2 compared to IFT-1, already at the start, when the engines reached their nominal operating mode, Pogo oscillations arose with the appearance of hydroacoustic perturbations in oxygen supply lines of the first stage. Due to rapid passage of this dangerous mode, the process didn't have time to fully manifest itself and spontaneously died out.

5. The next case of self-oscillations occurred at the first stage (booster) during boostback. This case turned out to be quite difficult to analyze. However, one can note that its main features, for example, such as turning off the engines before the explosion in turn in 2 steps with a significant break between them, the fact that the first 3 engines were being turned off on one side of the booster, and other 9 – after on the other side, were entirely obtained by solving equations using inaccurate quantitative data about the design of the booster. This indicates that the qualitative structure of the phenomenon is highly stable, and can be revealed even with such very imprecise quantitative information. Multiplicity of hull vibrations with hydroacoustic disturbances in the oxygen supply lines also played a role here.

6. The explanation for the occurrence of Pogo process, which led to the explosion of the second stage shortly before the completion of its acceleration phase of the trajectory, is extremely simple – positive feedback between hydroacoustic perturbations in the oxygen supply lines to the engines at their throttling and own oscillations of the second stage hull with a multiplicity of 2.

7. For individual rocket stages, no introduction of additional compartments can help. Now it is necessary to suppress hydroacoustic oscillations in the engines supply lines.

8. It can be noted that SpaceX continues to hide information about the manifestations of Pogo on Starship, and, obviously, has decided to carry out work to suppress dangerous hydroacoustic disturbances in propellant lines of the system under the guise of preparing for an experiment on transferring propellant in zero gravity (if they now have any definite opinion at all about the cases of explosions during IFT-2). Any such a pretext will delay the third flight, as SpaceX expects, for a sufficient time to carry out the necessary work. However, due to the fact that such processes were never previously calculated, carrying out measures to suppress them always took very much time.

9. In addition, the suppression of only experimentally discovered Pogo processes doesn't guarantee that new variants of them won't arise in new phases of flight which weren't tested in the flight experiments. In addition, any modernization of Starship system, such as increasing its length, mass, reducing wall thickness, or rising engine thrust due to increasing pressure in the combustion chamber, will lead to the fact that flight testing of the system will need to begin essentially again from the very beginning.

10. Thus, the use of numerical method proposed in paper [1] for calculating hydroacoustic oscillations in the fuel supply systems of liquid rocket engines with large pressure drops to identify Pogo processes is one of the necessary conditions for both the rapid and successful completion of Starship test program, and to evaluate other variants of this rocket system.

As a result, along with, apparently, the main achievement of 2023 – the creation and testing of reliable liquid-propellant rocket engines Raptor-2 with extremely high performance as part of the power plant of Starship, as well as the almost complete testing of its acceleration, previously unforeseen obstacles arose in the path of its development in the form of the emergence of self-oscillations of Pogo-type, leading to explosions of engines that find themselves in conditions in which rocket engines can't operate in principle. The first such process, discovered in the first flight, was suppressed, however, instead of it, in the second flight, already 3 unforeseen processes of the same type arose again, and what was done to prevent the very first Pogo process couldn't be used to suppress them. And how many such processes may arise during the development of yet untested parts of Starship full flight program, as well as during its modernization, no one now knows. Therefore, it seems that the most necessary tool for the successful development of this rocket system should be one that is capable of predicting and assessing these Pogo processes in the present and future.

III. Why is Pogo processes analysis so important for Starship?

Pogo-type self-oscillations have previously created great difficulties for developers of various rocket systems. Moreover, there is a well-founded opinion that it was Pogo during fourth launch that not only interrupted the flight of Soviet N1 lunar rocket, which was passing practically without problems for the first time, but also led to the closure of its development program [4]. However, the impact of Pogo on a rocket system has probably never been as great as it is on Starship.

This is due to the following circumstances: Pogo occurs when the frequency of own elastic oscillation of the rocket hull (or its stage) is close or almost a multiple of hydroacoustic perturbations frequency in its fuel system. The rocket has one hull, and its own frequency is more or less defined. It, of course, changes after the stages are separated, but then they have fairly definite frequencies of their own oscillations.

However, path chosen by SpaceX, although it gave immediate results, apparently turned out to be a road to nowhere, which, it seems, E. Musk himself has finally begun to understand. The rocket has only one hull, and it is possible to replace its own frequency with inserts, but only with another fixed one. And from the hydroacoustic side, a whole orchestra plays in favor of Pogo. Firstly, in rockets with liquid rocket engines there are always 2 potential hydroacoustic oscillatory circuits – fuel and oxidizer. Second, on multi-engine rockets like Starship, different groups of engines may have slightly different lengths for different propellant supply line configurations, which mean there may be multiple oscillating circuits with slightly different frequencies. Thirdly, due to the reusability of Starship, there was a requirement to create Raptor-2/3 rocket engines with the highest performances. They have record pressures in the combustion chamber, and, therefore, record pressure drops at the pump. In addition, they also have an unusually wide range of operating thrusts, and, accordingly, pressures. And as the theory created in May of this year after IFT-1 shows, at high pressure drops in the pump, the frequency of hydroacoustic oscillations is approximately inversely proportional to the square root of the pressure drop. Thus, with a strong variation in engine thrust, the frequency of hydroacoustic oscillations also changes significantly. Fourthly, Pogo can occur not only when hydroacoustic and "elastic" frequencies resonate, but also when there is a multiplicity, which increases the number of possible dangerous oscillatory modes by at least 3 times. Fifthly, reusable stages must operate without Pogo and during their individual return, when the role of the interstage insert is reset to zero, and the frequencies of own elastic oscillations become completely different than during the acceleration of rocket stages in the assembly.

Thus, this orchestra isn't just played in favor of Pogo; due to the reusability of Starship, real virtuosos with a very wide range of their playing grow up there. And the more perfect the rocket system, the higher the characteristics of its engines, the more requirements are placed on the system in order for it to be reusable, the more virtuoso their game becomes. And it becomes impossible to resist all of them using a tool that can only change the own frequency of elastic vibrations once. In fact, this is what IFT-2 experiment demonstrated. And it becomes impossible to resist all of them using a tool that can only change the own frequency of elastic vibrations once, as was done by introducing the hot separation compartment (FHSI). In fact, this is what the IFT-2 experiment demonstrated. It is necessary to change hydroacoustic frequencies. In principle, it is known how to do this (see [4, 5]). But at the same time it is necessary to have their values, and until now this has only been achieved experimentally, which has extremely complicated such work. The calculating method can dramatically simplify this activity, greatly reducing time and other costs.

IV. A time to throw stones

Let's now try to assess what can be expected from SpaceX under Starship program in the near future. Of course, the outside observer knows little about what is happening there now. However, something can't help but seep out, and it is up to analyst to connect seemingly disparate and contradictory signals. Moreover, the first cycle: IFT-1 flight – SpaceX reaction to it, which lasted more than six months, has now fully completed, and can be used as a standard for assessing the company's behavior in the near future.

This cycle followed the model of A. Toynbee [6] in the mode: challenge – response. The direct threat identified in IFT-1 was properly recognized and addressed by introducing an additional element into Starship system. At the same time, the threat was hidden from the outside world, and also, highly likely, from the government regulatory and licensing organization – the FAA. In addition, as IFT-2 result showed, analysis and action ended on the first turn of the game with nature – on its turn in the form of a Pogo of assembly in IFT-1, the counter move eliminated the direct threat, but nothing was done to consider the options possible responses from the opposite side to the move made.

And they weren't long in coming. Three new threats of the same type appeared at once. In this regard, the very first statement by E. Musk that Starship would be ready for the third flight (IFT-3) "three to four weeks" after IFT-2 [7] was soon supplanted by messages that during IFT-3, an experiment will be conducted to transfer propellant components in zero gravity [8] (if, of course, Ship reaches orbit this time), which pushes back IFT-3, "definitely to the first quarter of 2024" [9] – everything again becomes very similar to what was said and done in the period of time between IFT-1 and IFT-2, which from "six to eight weeks" [10] gradually stretched to thirty.

It is also interesting to note that Kathy Lueders, who was appointed in May of this year to the position of Starbase head, stated 3 weeks after IFT-2 (December 12) that "Starship's anomaly investigation team was still looking into why the Nov. 18 flight's Automated Flight Termination Systems were activated" [9], despite the fact that by that time it's completely clear to an unbiased analyst that searching for the reason for activation of these systems is like searching in a dark room for a black cat, which isn't there. So, with the way things are going in Starship program now, it will be a long time before it reaches to orbital propellant refueling.

Sweeping trash under carpet also contributes to this. Probably, at first this was due to the fact that, according to SpaceX contract with NASA, by the end of 2024 the ability of lunar version of Starship to land on the Moon was to be demonstrated [11], which is impossible without propellant transfer in orbit. Despite the fact that this date has recently been officially moved to a later date [12], unforeseen problems identified during the tests, and calling into question even the shifted deadlines, cause tension among the company's senior management, which doesn't contribute to a fundamental resolution of the problems, but gives rise to new ones, as well as attempts to hide them from everyone. Moreover, the latter, unlike the first, seems to have worked out quite well so far. But, as the scripture says, everything comes to end: "There is an appointed time for everything... to throw stones and a time to gather stones".

Conclusions

1. During the first test flight of Starship, at acceleration of the system in assembly of two stages, a self-oscillating process of Pogo-type was detected, which led to the destruction of the rocket system. By introducing a hot separation interstage (FHSI), these oscillations were suppressed in next flight.
2. However, in the second test flight this didn't prevent three new types of similar oscillations arising, which caused explosions of both stages of the system after their successful separation.
3. Judging by the statements of SpaceX senior management, even almost a month after the second flight, the reasons for these incidents were unknown, although according to some data for the period from December 11 to 16, 2023, information about this must be received by them.
4. At the same time, the company's policy until now, as far as this can be judged from the outside, has been to hide from the outside world all information that could be hidden, attempts to pretend that all the processes in Starship program are under their complete control, as well as a reluctance to get acquainted with other approaches to assessing what is happening.
5. It is quite obvious that such actions by the company's senior management don't contribute to the successful development of this program.

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