Secrets of Starship test program: Analysis of its first phase main problems

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Summary

This paper describes five uniform critical problems that arose in first four launches of Starship, which led initially to detonation of this rocket system, then to failure of its trajectory, and in three cases to explosions of its stages in flight. Methods for solving these problems are considered, in most cases based on theory of rockets longitudinal auto-oscillations of pogo-type, and which is a derivative of hydroacoustic auto-oscillations theory in penstocks of hydroelectric power plants. It is shown that SpaceX (Starship developer) used the following typical algorithm to solve these problems: receiving data on the emergency process via telemetry during the flight, and changing the engine operating mode in the next launch so that the frequency of hydroacoustic oscillations leaves pogo zone. Then the flight is either successfully completed or continues up to next accident, with a repetition of these actions in the future until all these incidents stop.

SpaceX gained access to elements of pogo theory, in which described dependence of hydroacoustic oscillations frequency on the engine operating mode for a fixed fuel system geometry, in late 2023 – early 2024, between the second and third Starship launches. At the same time, it tried to make any data on this theory inaccessible to the public. Due to the fact that SpaceX doesn't have complete information about this theory, boundaries of areas of pogo occurrence and development will be shifted on new versions of Starship due to changes in their design characteristics. And this can lead, and has already led, to both the re-emergence of the critical problems described in the work, and to appearance of new problems caused by attempts to solve previous problems, which is confirmed by the seventh and eighth emergency flights of this system.

Keywords*: pogo, auto-oscillations, Starship, superspikes, frequency, resonance, multiplicity*

I. Introduction

On April 20, 2023, first test launch of Starship system, consisting of first stage (booster) – Super Heavy and second stage – ship of the same name (hereinafter referred to as simply Ship) [1], was carried out from launch site at Star Base near Boca Chica – Texas settlement on the coast of the Gulf of Mexico. This system, developed by SpaceX, should in the future become a multifunctional, fully reusable super-heavy launch vehicle designed to deliver cargo and people into low-Earth orbit. In addition, after orbital refueling, the second stage should turn into a spacecraft for flights to the Moon and Mars [2]. Then began, as it became obvious, a long process of transforming, using agile methodology, prototype of this system either into a sample brought to regular use, or, at best, into a museum exhibit.

The presented work analyzes the first 4 test flights of Starship, and reveals the key problem solved by the company during their execution, but not even officially announced and, practically, unknown anywhere outside of it. Is this so? We will present to readers, if not quite well-known, then at least publicly available information.

It should be noted that the last, seventh and eighth flights of the system, as predicted at the analysis of its flights during the first phase of testing [3], return again the problems, which seemed to have been eliminated after its completion. This is due to the fact that in the process of modernization and development of Starship system, which is absolutely necessary for the creation of its full-fledged version, the solution to the problem described below will be required again and again.

II. Features of Starship first four flights

First, let's briefly review the main features of Starship first four flights that are directly relevant to the problem under consideration here.

First flight (IFT-1), April 20, 2023

It was characterized by engine shutdowns (there were at least 6 of them), fires, telemetry failures, and, finally, impressive somersaults with the integrity of the entire system preserved, its detonation, which, however, didn't destroy it, as expected, and its final transformation into a pile of debris only upon entering sufficiently dense layers of the atmosphere [4, 5]. One can also note the severe destructions at the launch pad. However, all this was for us secondary, side effects – the fundamental process that led to almost all these phenomena wasn't only described by SpaceX, and not noticed by almost no one, but wasn't mentioned at all in either SpaceX press releases or in the mass-media. This is a completely unusual, "ragged" flight of Starship practically from the very start to the very end.

It can be seen most clearly in the graph of trajectory data of this rocket system, see Fig. 1. It shows four parameters: acceleration of Starship rocket (in cm/s^2), speed (in m/s) and flight altitude (in hundreds of meters), as well as number of working engines (in the graph it is multiplied by 10 to obtain a comparable scale of the curves). This graph appeared on the network on the same day as a result of processing data from additional windows of video stream [6], and it finally convinced the author of this work that his visual impression of the nature of Starship flight from monitor screen was correct. It soon became clear that this phenomenon wasn’t an artifact of inadequate operation of data measurement and display system (much later this was described in paper [7]).

Thus, in Fig. 1 it can be seen (see the purple line with sharp peaks) that throughout the entire part of the system's trajectory where controlled flight took place, the rocket experienced sharp acceleration fluctuations with a period of 12 seconds, expressed in a form of at least 10 pairs of narrow peaks, first a sharp drop in acceleration almost to 0, and then a very rapid increase. These specific pairs of peaks were called superspikes by analogy with the names of outwardly similar pairs of peaks in stock market trading – closely spaced spikes of seller and buyer, directed downwards and upwards, respectively.

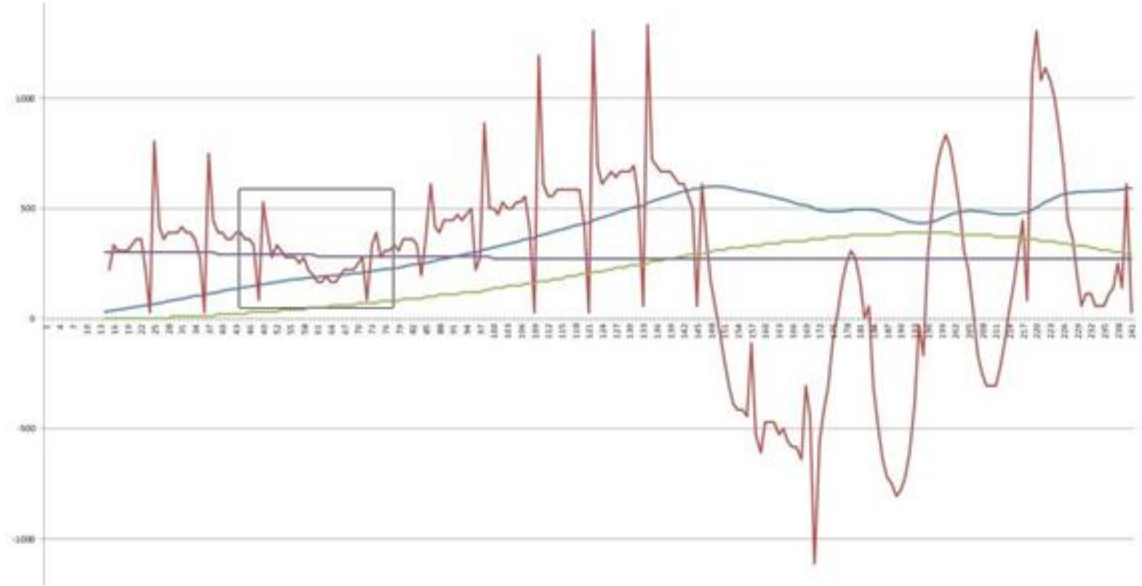

Fig. 1 – Acceleration. speed, altitude and number of working engines of Starship

It should be noted that in max Q zone during IFT-1 there is no superspike, which should have been there in accordance with the period of their appearance of 12 seconds (zone of our interest is highlighted in the figure with rectangular boundaries). This superspike was "missed". Why? The answer to this question will be given below. Closely related to this moment is the radical change in Starship separation scheme after first flight – from "cold", when the second stage engines are turned on after the first stage engines are turned off, to "hot", when the stages are separated while those engines are running (or at least part of them) [8]. The advantages and disadvantages (especially in reusable systems) of each of the options are quite obvious, and won’t be discussed here. It should only be noted that this decision was made in violation of the principles of agile methodology, since the initial stage separation scheme wasn’t tested during the first flight.

After the first flight, public's attention was drawn to 63 "corrective actions" needed to obtain a license from the FAA for the second flight [9], and, in general, although useful, but often quite minor, but main "corrective action" – the appearance of interstage hot separation compartment was glossed over, and explained by the desire to increase mass of payload launched by the system. Although, then there were clearly no resources to solve the payload issues back then, and up to the present time, 2 years later, already on new enlarged version of the system, payload, which equals 4 mock-ups of Starlink satellites [10], is clearly not impressive. Why did the intermediate compartment appear exactly then?

However, leaving this question unanswered for now, we will continue our review and move on to the second flight of this system.

Second flight (IFT-2), November 18, 2023

The second flight of Starship, although was much more successful than the first, nevertheless, in terms of results, it also turned out to be a unique – at different times, 2 explosions occurred, which separately destroyed both stages of the rocket system [11]. The acceleration of the assembly of two stages took place without any comments, superspikes could be forgotten as a bad dream – this is what was achieved with the help of the only significant change in the stack design – introduction of an intermediate interstage compartment. Hot separation also turned out to be completely successful. After this, the first stage (booster) went into boostback – a braking maneuver to return to launch site and, having started only part of the engines, exploded at the finish of this maneuver (Fig. 2, see thick yellow line – acceleration graph) [11]. Note that after the booster turn, the accelerations that are in Fig. 2 shown as negative, but in reality they became positive (they were pressing fuel to the bottoms of tanks).

During the boostback, 4 engines out of 13 failed to start, and when the turn was completed and a relatively calm flight without rotations began, local explosions and fires began on the booster, and then a general explosion, after which it was blown to pieces [12] (zone of thrust loss, ending in an explosion, is highlighted by a rectangle in Fig. 2). We should also note serious fluctuations in acceleration at the very beginning of acceleration, when the power plant was just reaching its nominal operating mode.

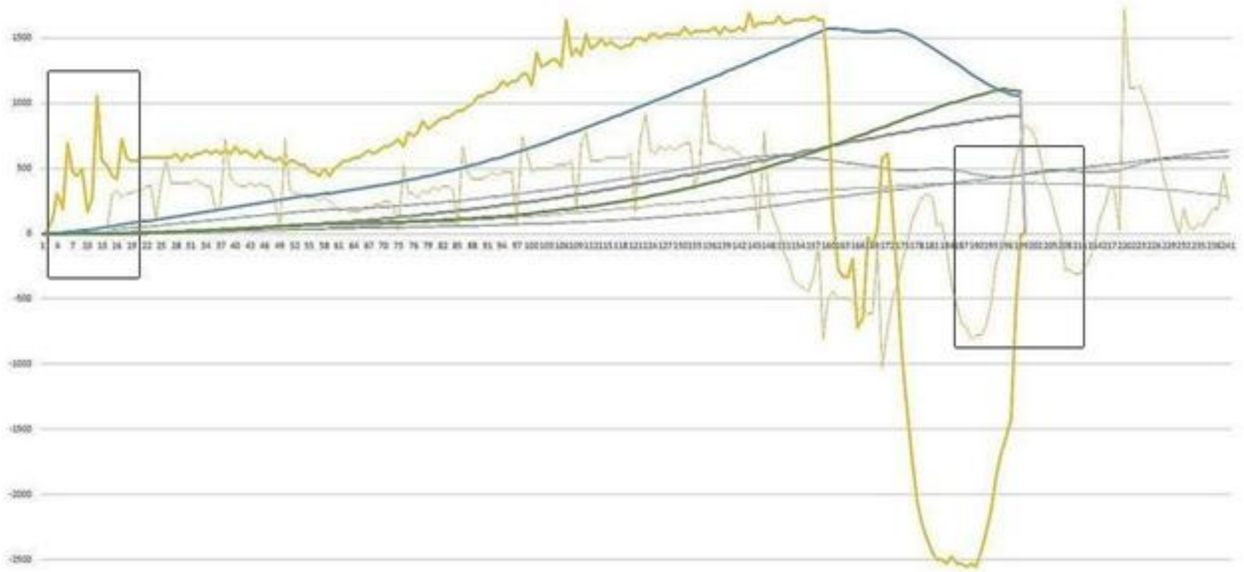

Fig. 2 – IFT-1 (stack) and IFT-2 (booster) flights, acceleration during IFT-1 is a thin line with superspikes (see Fig. 1), acceleration of the booster during IFT-2 is a thick yellow line with sharp ledges (speeds, altitudes and flight ranges are also shown)

At the same time, the second stage (Ship) accelerated quite successfully in accordance with the flight program, until, shortly (30 seconds) before the end of acceleration, it suddenly exploded spontaneously [13]. Apparently, this was the first launch in history with two completely separate explosions of two parts of launched rocket. 23 seconds before the explosion, a certain amount of boosting gas from stage oxygen tank was released, apparently to ensure that the pressure at the inlet to the rocket engine pumps was close to the nominal. The plume of the released mixture of carbon dioxide, water vapor, small impurities of unburned and not fully oxidized fuel residues with a significant predominance of oxygen dissipated without a trace in the surrounding space in 2 – 3 seconds [13].

For at least two months, SpaceX management claimed that the cause of the second stage's loss during IFT-2 was either an abnormal activation of its detonation system or that very same pressurization vent. Kathy Lueders, head of Starbase, reported on December 12, 2023: "Starship’s anomaly investigation team was still looking into why the Nov. 18 flight’s Automated Flight Termination Systems were activated" [14]. Then followed a month of silence, and finally Elon Musk announced on January 12, 2024: "...the reason that it [Ship] actually didn't quite make it to orbit was we vented the liquid oxygen, and the liquid oxygen ultimately led to fire and an explosion". Of course, the vented boost gas wasn’t any "liquid oxygen". There were no statements at all regarding the reasons for the booster explosion.

Third flight (IFT-3), March 14, 2024

The third flight was originally expected to take place in the second half of February 2024, but then there was a 3 – 4 week delay that was never commented on anywhere, and a new copy of Starship flew in mid-March [16]. This time, by changing the algorithm for starting the power plant at the start, it was possible to get rid of significant acceleration fluctuations (and, accordingly, thrust), and in addition, the booster almost completely successfully passed the boostback and went to land on the water surface of the Gulf of Mexico, but exploded during the final braking by the engines (see the rectangular zones at the edges of the graph in Fig. 3) [17].

The success of the boostback was due to the throttling of the engines, which led to a decrease in the thrust of each of them by ~ 1.2 times. However, the number of operating engines increased from 9 to a maximum of 13, and their total thrust and, accordingly, the acceleration of the booster increased by about 1.2 times, see the area highlighted by a rectangle near the center of the image in Fig. 3. However, at the very end of braking, 6 engines still chaotically switched off 2 – 3 seconds before the planned time, the booster was slightly turned around, it ended up on a steeper return trajectory and didn't reach the calculated splashdown point [18].

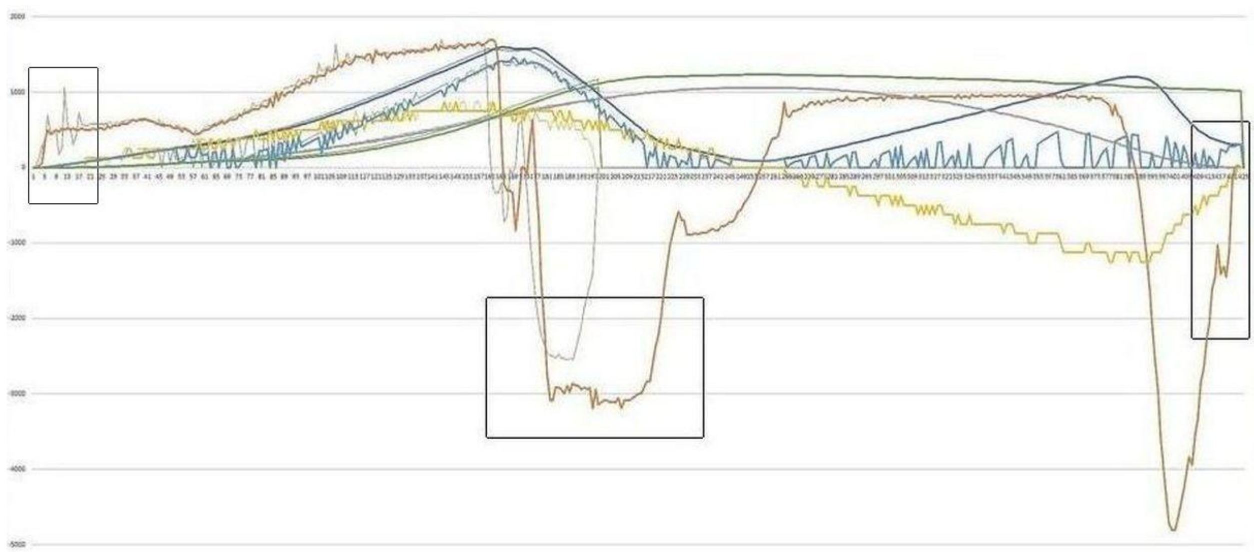

Fig. 3 – IFT-2 and IFT-3 flights (boosters), acceleration is thin and thick purple lines at IFT-2 and IFT-3 respectively, with sharp ledges

On the second stage in the third flight, ventilation of oxygen tank wasn't noticed, in addition, the most efficient engines with vacuum nozzles in those conditions were switched off in advance, which led to a completely successful end of acceleration [17], see the two rectangular zones in Fig. 4. The left one is the completion of acceleration in the second flight, and the right one is in the third.

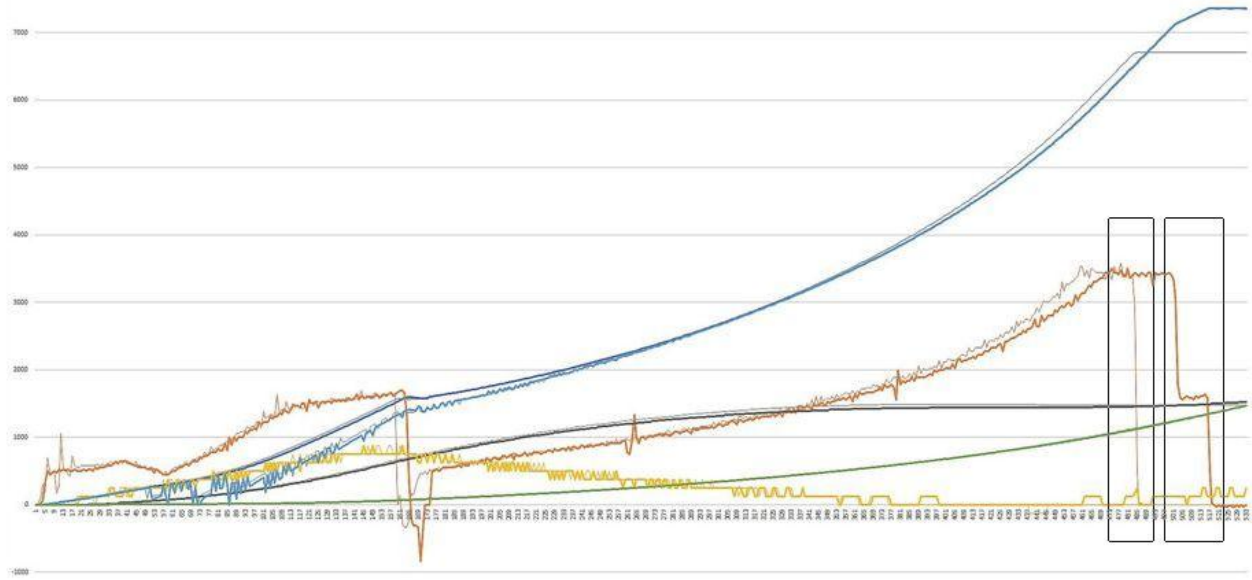

Fig. 4 – IFT-2 and IFT-3 flights (second stages), acceleration is thin and thick purple lines at IFT-2 and IFT-3 respectively, with sharp ledges

Shortly after this flight, on April 4, 2024, Elon Musk spoke again at the launch site to Starbase employees, as he did on January 12, but in a completely different tone. In January, he tried to explain the problems that arose during Starship testing, and in April, there was a speech by the winner, who received the key to solving them, about flights to Mars [19].

Fourth flight (IFT-4), June 06, 2024

This flight essentially completed the development cycle of Starship first version of to the point where it could complete its planned flights without explosions, with soft landings of both stages on the water (and then the booster on the launch and landing complex) and explosions there, on the surface of the water [20]. Of the points of interest to us, we should pay attention to the return of intense acceleration oscillations (and, accordingly, thrust) at the start, see the leftmost zone in Fig. 5. Obviously, this was due to another algorithm for starting the power plant of 33 rocket engines.

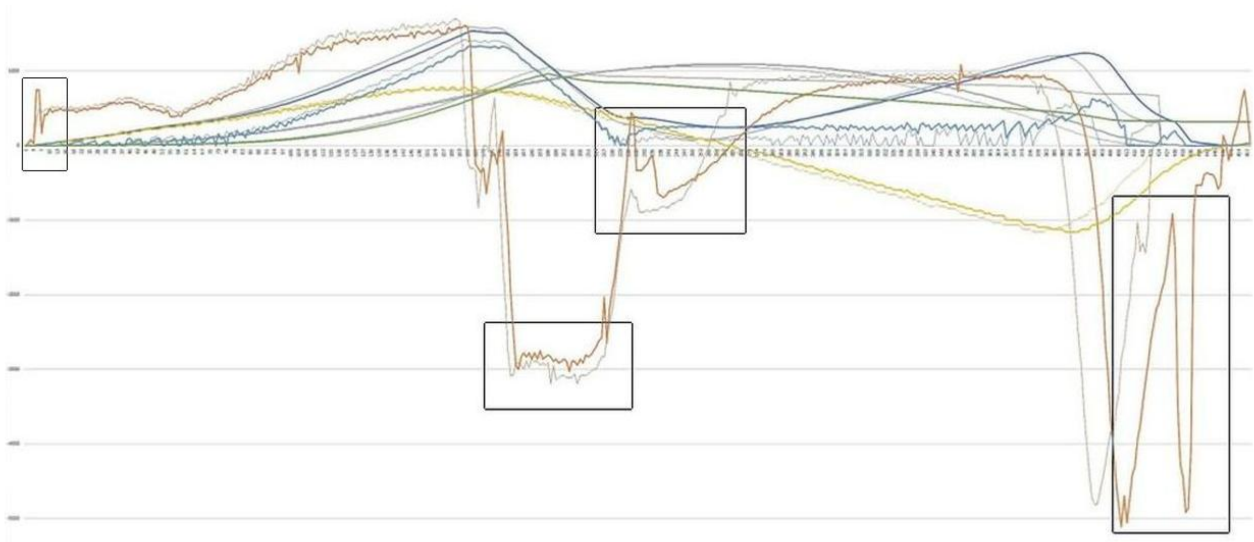

Fig. 5 – IFT-3 and IFT-4 flights (boosters), accelerations are thin and thick purple lines at IFT-3 and IFT-4 respectively, with sharp ledges

During the boostback, the engine thrust was reduced by a few more percent, which ultimately resulted in their required operation during all this maneuver (see the rectangular zones in the center of Fig. 5), due to which the return of the booster to calculated splashdown point was ensured near the buoy with the TV camera, which was previously placed there (see zone on the right side of Fig. 5). In addition, shortly after the boostback, the intermediate compartment, weighing about 9 tons, was jettisoned from the booster [21], after which its speed, due to aerodynamic braking at the moment of final activation of the engines, was lower by about 15 %, and, working at reduced thrust, they not only didn’t explode, but also ensured the first soft splashdown of the booster. True, it then exploded while floating on the surface of the water, but, apparently, this was a planned event. On the next, fifth flight, a copy of the booster was successfully captured by side consoles of the launch and landing complex and returned back for the first time practically intact [20].

The second stage at IFT-4 performed almost the same acceleration as its predecessor at IFT-3, only 3 engines with vacuum nozzles were switched off ~ 10 s earlier. Its further flight in unclosed orbit, braking in the atmosphere with the burning off of front flaperons and a successful rocket soft landing on water [20] are beyond the scope of the issues considered here.

III. List of problems and contradictions identified during the first phase of Starship flight tests

Let us briefly summarize the most important problems, contradictions and logically difficult to explain events of spring 2023 – summer 2024, described in the previous section of this paper. These include:

1. The completely unusual, "ragged" flight of Starship during the first launch, accompanied by failures, fires and explosions, with clearly repeating "superspikes" every 12 seconds.

2. Transition to "hot" separation of stages, seemed absolutely irrelevant, but in fact, completely justified.

3. Almost simultaneous explosions of both stages during the second launch and rather helpless attempts to explain them by management of SpaceX for at least two months after it.

4. Change of priorities from the beginning of February 2024 – delay of third launch by 3 – 4 weeks.

5. Almost completely successful passage of two critical events of the second launch during the third launch, and, at the finish, explosion of the booster during braking before splashdown, in a situation that had seemingly already been worked out twice.

6. Tweaking of the boostback procedure and successful splashdown of the booster in the fourth launch with by nobody explained jettison of the intermediate compartment, which nevertheless ended with booster exploding after splashdown.

7. And the absolutely opposite tonality of Elon Musk's speeches at the launch site on January 12 and April 4, 2024 – before and after Starship third flight, although both times boosters exploded in the sky in the last flights before these speeches.

IV. Auto-oscillations of pogo-type – a unified explanation for all these events and phenomena

Pogo oscillations are dangerous auto-oscillations of rockets along their longitudinal axis with a frequency of, usually, 5 – 20 Hz, which can occur in a system consisting of an elastic rocket hull and liquid in its fuel lines [22]. Rocket engines, consuming fuel from the lines, respond to fluctuations in its consumption, which causes thrust fluctuations, creating elastic oscillations of the hull, which in turn affect the fuel consumption. Thus, a positive feedback is created between oscillations of liquid (usually only one of fuel components), and elastic solid body (rocket structure or some of its elements, for example, unit transmitting engines thrust to its structure) [5].

And if frequencies of these two types of oscillations are close or multiples, they become undamped, and in many cases their rapid growth can be observed when the energy supply to this process from the operation of the power plant exceeds its natural dissipation. Then the increase in the amplitude of oscillations will continue until dissipation in the system will become equal to energy supply to it from an external source (in the case of pogo – energy of burning fuel), or until system will change its operating mode (for example, engines will be turned off), or it will cease to exist (rocket vehicle will be destroyed). There were serious problems with the mathematical modeling of such hydroacoustic oscillations, because in the model of such processes there must be discontinuities simulating operation of pump. But classical solutions are smooth. In this regard, these auto-oscillations were previously fought, mainly, using experimental methods [23].

However, it turned out that in penstocks of hydroelectric power plants there are also similar water oscillations, which, together with oscillations of cavitation cord arising behind the turbine when it operates in an off-design mode, form two interacting processes that lead to destructive auto-oscillations. The most famous and striking example of this kind was Sayan disaster – takeoff the second hydroelectric unit of the most powerful Sayano-Shushenskaya hydroelectric power plant in Russia from turbine pit on August 17, 2009, the destruction of station machine room and death of 75 people [24]. This event greatly stimulated work on modeling discontinuous solutions of hydroacoustic oscillations [25, 26].

In the period from late April to early June 2023, immediately after Starship first flight with superspikes, the author of this work changed the equations describing hydroacoustic oscillations in penstocks of hydroelectric power plants (HPPs) so that they adequately reflect similar oscillations in the feed lines of liquid rocket engines. This required a replacement in one of boundary conditions. It immediately became clear that in this version, theory of hydroacoustic auto-oscillations in penstocks of HPP, at least in terms of calculating the key parameter – frequency of hydroacoustic oscillations, can be easily transformed into theory of pogo-type oscillations. In the first tests, the calculated characteristics of the processes were compared with known data on to two cases of pogo occurrence on Saturn V lunar rocket in 1968 and 1970 (5 and 15 Hz, respectively). Everything came together perfectly – the same pogo frequencies were obtained as in nature [5], see Table 1. Thus, the verification of the numerical model was successfully carried out.

Table 1 – Frequencies of hydroacoustic oscillations during pogo-type auto-oscillations on first (S-IC) and second (S-II) stages of Saturn V lunar rocket

Rocket Stage Engine	**p_2/p_1**	**L_1 (m)**	**L_2 (m)**	**L_3 (m)**	**L_{eq} (m)**	**f_n (Hz)**
c = 845 m/s						
Saturn V S-IC F-1	24.5	1.36	13.40 + 3.51	18.27	40.5	5.21
		1.51		18.42	42.3	**5.00**
		1.66		18.57	44.0	4.80
c = 835 m/s						
Saturn V S-1I J-2	28.5	0.90	2.92	3.82	13.9	**15.0**

In the table, c is the speed of sound in liquid cryogenic oxygen, p_2/p_1 is degree of pressure increase on the oxygen pumps of F-1 and J-2 engines, L_1 is the length of oxygen line from pump to gas generator, L_2 is the length of oxygen line from tank to the pump, L_3 is their sum, L_{eq} is the equivalent length of the oscillatory circuit, that is, the length that corresponds to the frequency of oscillations that occur in it in the absence of the pump, f_n is the frequency of hydroacoustic oscillations of liquid oxygen.

And by the end of May 2023, the new theory had already begun to be used in the application to analysis of Starship behavior. Frequencies of elastic oscillations f_e of objects approaching the pipes in their structure were recalculated from known samples (Saturn V and Titan II GLV rockets) using the similarity formula for such objects:

$$f_e = \kappa \sqrt{\frac{\pi E D \delta}{m L}},$$

where κ is the proportionality coefficient, according to experimental data of the order of 1, E is modulus of elasticity of material, D is diameter of stage, δ is thickness of its wall, m is mass of stage or stack, L is its length or length of stack.

And soon Elon Musk began talking about the interstage hot separation compartment, and this showed that SpaceX also understood what had happened in the first flight [8]. The introduction of this structure between the stages of Starship, due to its thick walls and bottom, significantly more rigid than the stages themselves, sharply changed the frequencies of system elastic vibrations, and brought them out of multiplicity with the frequencies of hydroacoustic oscillations. As a result, the occurrence of pogo in flight of modified version of stack became impossible.

Using the new algorithm, first tens and then hundreds of calculations were carried out, and it turned out that with large pressure drops in the oscillatory circuit, the frequency of hydroacoustic oscillations f_n, is approximately inversely proportional to the square root of the ratio of pressures at the pump p_2/p_1 [5, 17]:

$$f_n \sim \sqrt{\frac{p_1}{p_2}} \qquad (1)$$

It should be noted right away that formula (1), extremely simple in its structure, became key for further analysis of the course of events during the first phase of Starship testing.

V. Blocking information about pogo and method of its calculation

During the summer and early fall, preparations were underway for the second Starship flight, this time with the intermediate hot separation compartment. During this process, on August 7 and 25, two ground static fire tests of Starship first stage (Super Heavy booster) power plant were conducted, with a full complement of 33 Raptor-2 engines [27, 28].

Against this backdrop, author of this work submitted his first article on pogo theory to the well-known resource arXiv.org on October 5, 2023, in which was analyzing the results of Starship first flight. Among other things, it described for the first time in the public domain the relationship between the frequency of hydroacoustic oscillations in the fuel line of a rocket engine and pressure drop on its pump. This article was supposed to be published on October 9, but at the last moment it was unexpectedly delayed for an unprecedented period for the archive under various excuses, clearly used to drag out time. Finally, already in November, shortly before Starship second flight, more than a month after its submission, arXiv, in violation of the usual procedure applied to publication delays, without even the slightest attempt to find out anything from author, decided not to publish the article. The following reasons were officially given: "Our moderators have determined that your work is devoted to a topic not covered by arXiv, or that the target audience of your work is not the community we currently serve". In general, think what you want, we suppose that no one needs to know this, and we won't tell you anything more [17].

A month later, on December 6, 2023, the author posted a short summary of the article rejected by the anonymous arXiv moderators as his first post on NSF aerospace forum (NasaSpaceForum), that is, he wrote a few lines about it. This short text caused such a heated discussion on NSF that it soon almost completely displaced all other issues considered there in the thread about Starship second flight. In connection with this, on December 15, in order to continue the discussion of this issue, one of the forum participants (not author) created a separate topic, which, without explanation, was closed on the same day, 13.5 hours later, and the author was denied access to the forum, whose connections with the SpaceX company are easily traced [17].

Moreover, it soon became clear that the author had been blocked from accessing an unspecified number of administrative and informational websites throughout Cameron County, Texas, where SpaceX economic influence is dominant, and even from website of the county's leading newspaper, the Brownsville Herald [17].

If at least two of these nearly simultaneous events are not random, then the only obvious actor interested in them, that is, in blocking information about the occurrence of pogo in Starship, as well as in hiding data on the simple connection between the frequency of hydroacoustic oscillations and characteristics of fuel system, is SpaceX.

At the same time, an analysis of the events that occurred in the programs of the third and fourth Starship flights showed that, based on post-accident data and using the above formula (1) for recalculating the frequency of hydroacoustic oscillations in the fuel lines of both stages, in subsequent flights SpaceX company began to suppress the excitation of auto-oscillations detected in the previous flight by changing operating modes of rocket engines.

VI. Five critical pogo-related problems in the first four Starship flights, five solutions and their explanation

Based on the list of problems and contradictions identified during the first phase of Starship flight tests, presented in Section III of this paper, we formulate 5 main problems that, according to theory, were caused by various variants of pogo-type auto-oscillations.

Problems

1. A completely unusual, "ragged" flight of Starship during the first launch, accompanied by failures, fires and explosions, with clearly repeating "superspikes" every 12 seconds.

2. Excitation and spontaneous termination of auto-oscillations at the start, recorded during the second and fourth launches.
3. Explosion of the booster during the second launch and premature asymmetric shutdown of the inner ring engines during the third launch under boostback.
4. Explosion of Ship (second stage) at the end of acceleration during the second launch.
5. Explosion of booster at the moment of splashdown during the third launch.

Let's briefly describe how these problems were solved by SpaceX.

Solutions

1. Introduction of an interstage hot separation compartment.
2. Reduction of the rate of increase in engine thrust at the initial and final stages of the process of reaching nominal thrust and an increase in the rate of rise in thrust at the middle stage of this process.
3. Two-stage reduction of engine thrust during boostback.
4. Refusal to dump the boost gases of the ship's oxygen tank and shutdown of the ship's engines designed for operation in a vacuum at the end of acceleration.
5. Dumping the interstage hot separation compartment after boostback and, as a result of this measure, a corresponding reduction in engine thrust during final braking.

Now, using pogo excitation theory, we will briefly explain why these solutions made it possible to eliminate the identified problems.

Explanation of mechanisms that caused pogo and impacts of taken decisions

1. During the first flight, auto-oscillations of pogo arose with a frequency of 5.5 – 6 Hz, excited by hydroacoustic oscillations in methane feeding lines with a frequency of about 2 Hz. The slowly developing process was countered by the control system, which began to reduce engines thrust and, accordingly, pressure in the combustion chamber, as well as the pressure drop of methane flow on the pump. This increased the oscillation frequency and temporarily stopped pogo. After the engines returned to the nominal operating mode, it returned the system to its original state. The insertion of the intermediate compartment broke the unified elastic oscillatory circuit – an assembly of two stages, greatly increased the elastic frequency of the structure, and eliminated pogo of the stack.
2. Increase in speed of thrust gain at the start at the moment the conditions for pogo arise didn’t allow it to develop noticeably.
3. Reducing engine thrust during boostback increased the frequency of hydroacoustic oscillations and took it out of pogo zone.
4. Refusal of ship's oxygen tank ventilation in the final phase of flight led to a decrease in the pressure drop on the pumps, and, therefore, to an increase in the frequency of hydroacoustic oscillations in the engine feeding lines. Nevertheless, even under such conditions, the external engines had to be turned off at the end of acceleration.
5. Jettisoning the heavy interstage compartment before start of final braking led to a decrease in the speed of booster at the moment of engine activation due to more effective aerodynamic braking, which made it possible to reduce their thrust. As a result, frequency of hydroacoustic oscillations increased, and pogo didn’t start.

Thus, from the analysis of data presented in the previous sections of this paper, it follows that in cases 1, 2, SpaceX independently resolved the problems associated with auto-oscillations. And when solving problems in cases 3 – 5, which were identified in the second and third flights, the following solution algorithm is quite clearly traced: after an object accident occurs in another one flight, or, at best, a failure of some engines, and the frequency of pogo oscillations becomes known from telemetry, the engine operating mode in the next flight in this phase of flight is recalculated according to formula (1) so as not to get into the pogo excitation zone this time. At least in one case – when working off boostback in the third and fourth flights, apparently due to approximate of this formula or some other circumstances, this algorithm had to be applied twice using the method of successive approximations. It should be remembered that SpaceX doesn’t have access to the full description of the theory and to the program for calculating hydroacoustic oscillations in rocket fuel systems.

Conclusions

1. All five critical problems of Starship in the first four flights were caused by the occurrence of various processes of auto-oscillations of pogo-type, which led to both the detonation of the rocket system and to the disruption of the trajectory, and in three cases – to the explosions of its stages in flight.
2. The problems that led to explosions of the stages and disruption of the trajectory were solved by changing in the fuel supply lines the frequencies of hydroacoustic oscillations to move them away from own frequencies of vibrations of the rocket structure.
3. The frequencies of hydroacoustic oscillations were changed by throttling the engine thrust (or, later, from the fifth flight, forcing), and in one of the modes – simply by turning them off.

4. The parameters of critical modes were determined during Starship flights at the moments of occurrence and development of excesses and transmitted via telemetry, and at the next launch, the engine operating modes were changed based on the experimental data from the previous launch and formula (1) for recalculating the frequency of hydroacoustic oscillations based on the pressure drop on the pump of the corresponding fuel component supply line from pogo theory.
5. SpaceX gained access to elements of pogo theory in late 2023 – early 2024, between the second and third Starship launches. At the same time, it tried to make any data on this theory inaccessible to anyone else..
6. Due to the fact that SpaceX doesn't have all the information about pogo theory, on new versions of Starship system, because of changes in their design characteristics, boundaries of pogo zones will be shifted And this can lead, and has already led, to both the re-emergence of the critical problems described in this work, and to appearance of new problems caused by attempts to solve previous problems.
7. The seventh and eighth flights of Starship with the second stage, in which the design was significantly changed for the first time, clearly and visibly confirmed correctness of previous conclusion.

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