Why did Starship second stage not explode in the ninth flight, but instead began to spin uncontrollably?

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Summary

This paper shows that the explosion of Starship second stage in ninth flight at operation end of three Raptor-2 side engines with vacuum nozzles, as happened in the eighth flight, didn't occur because engine thrust during this period was quickly increased to a level 15 – 20 % higher than before. Similar control of engine thrust with analogical goals and results occurred earlier, for example, in the fifth flight of Starship during boostback of its first stage. And absolute maximum of the second stage overload level in the ninth flight was equal to 4.3 – 4.4 compared to no more than ~ 3.5 units in all previous ones. In both cases, such control of power plant made it possible to quickly "skip" the dangerous zone of Pogo excitation associated with hydroacoustic oscillations in the liquid oxygen supply lines of the engines.

However, Pogo excitation process on second stage during shutdown of three central engines with conventional nozzles, as well as during shutdown of inner ring engines at boostback of first stage on third flight, couldn't be completely avoided. In this regard, one of them was switched off a fraction of a second before the other two, which caused the stage to begin an uncontrolled rotation. In addition, for at least several tens of seconds, there was a lateral leak of gas (judging by the colour, oxygen) through the wall of hull where no valves or holes were visible. This also contributed to further spinning of the stage, and at the same time reduced the amount of boost gas available to its attitude control system.

Therefore, the second stage entered the atmosphere in an unplanned manner and was destroyed for the third time in a row, preventing the achievement of main goal of the ninth flight – to test new solutions for heat protection, without which further progress of Starship project is impossible. Thus, it can be stated that this project is developing in response to constantly emerging new problems, and no attempts are made to foresee their occurrence in advance, although there are opportunities for this.

Keywords: *Starship, ninth flight, Pogo, crash, longitudinal auto-oscillations*

I. Introduction

Starship's ninth flight (IFT-9), or its third flight with a new version of the second stage (Starship V2 or Starship 2), which took place on May 27, 2025, universal time, in third year of test launches of this system, ended, like the two previous flights, in an accident [1]. Earlier, in eighth flight, launch and landing complex successfully picked up the first stage, but on the second stage, first one of its three side engines with vacuum nozzles failed, and then, immediately, all three central engines with conventional nozzles that control pitch and course failed also. After that, the two remaining side engines twisted the already uncontrollable vehicle, which soon broke up and burned up upon entry into the atmosphere [2].

During the ninth flight, first stage, which was making its second flight, exploded already, and this time it was supposed to splash on the water, having intentionally performed a return manoeuvre (boostback) under greater dynamic and thermal loads than during all five previous successful manoeuvres of this kind [3]. Most likely, this accident was in no way connected with Pogo problem, which is examined in detail and systematically in a series of papers, which includes this work. Apparently, either the strength limit of some structural element was exceeded due to more difficult return conditions, or forced fatigue failure occurred on the stage, which was already making its second flight. However, no real data on this boostback (including trajectory data, unlike all previous flights) has yet been received by the outside world, and any thoughts on this topic can't currently have any factual basis.

But some trajectory data related to the latter, key to understanding the causes of the accident in the final phase of second stage acceleration, are available [4]. In addition, a large array of experimental and calculated information has been accumulated in the previous 8 launches of the system. Therefore, despite the insufficiency and fragmentation of the available data, it is possible to draw quite reasonable conclusions about the causes of what happened. And from the analysis of the "corrective actions" carried out by SpaceX in the interflight period, which didn't represent, in essence, anything serious [5], at most – "additional preliminary load on key connections", it follows that the main question that needs to be answered is: "Why did Starship second stage not explode in the ninth flight, but only spin after its engines were turned off?"

II. Available trajectory's data

Due to change in form of data on altitude and flight speed presentation, as well as on amount of propellant in information window, in the video of the ninth flight, provided by SpaceX, the speed indications disappeared in trajectory phase of simultaneous flight of two stages [1]. Whether this is stupidity of interface "improvers", or consequences of the company's deliberate policy to reduce the amount of real information about flight for outside world, but now trajectory data available to us in the phase of second stage acceleration begins only from the seventh minute of the flight, see Fig. 1 [4].

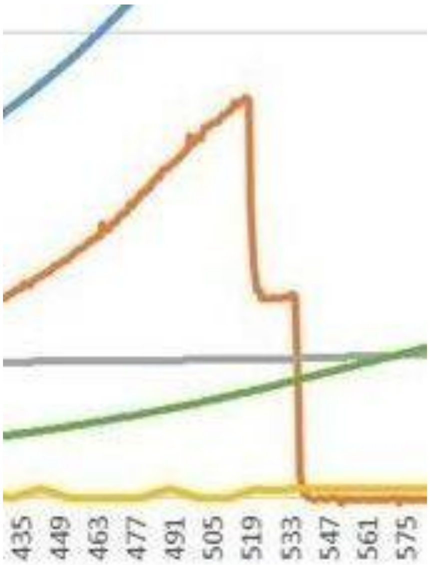

Fig. 1 – Acceleration (brown line with step) of Starship on ninth flight (IFT-9)

For analysis, it is advisable to superimpose acceleration data of the vehicle on similar information obtained during launches six through eight [6], see Fig. 2. Here, the white dots show the second stage acceleration in the ninth flight during the final phase of its boost according to Fig. 1.

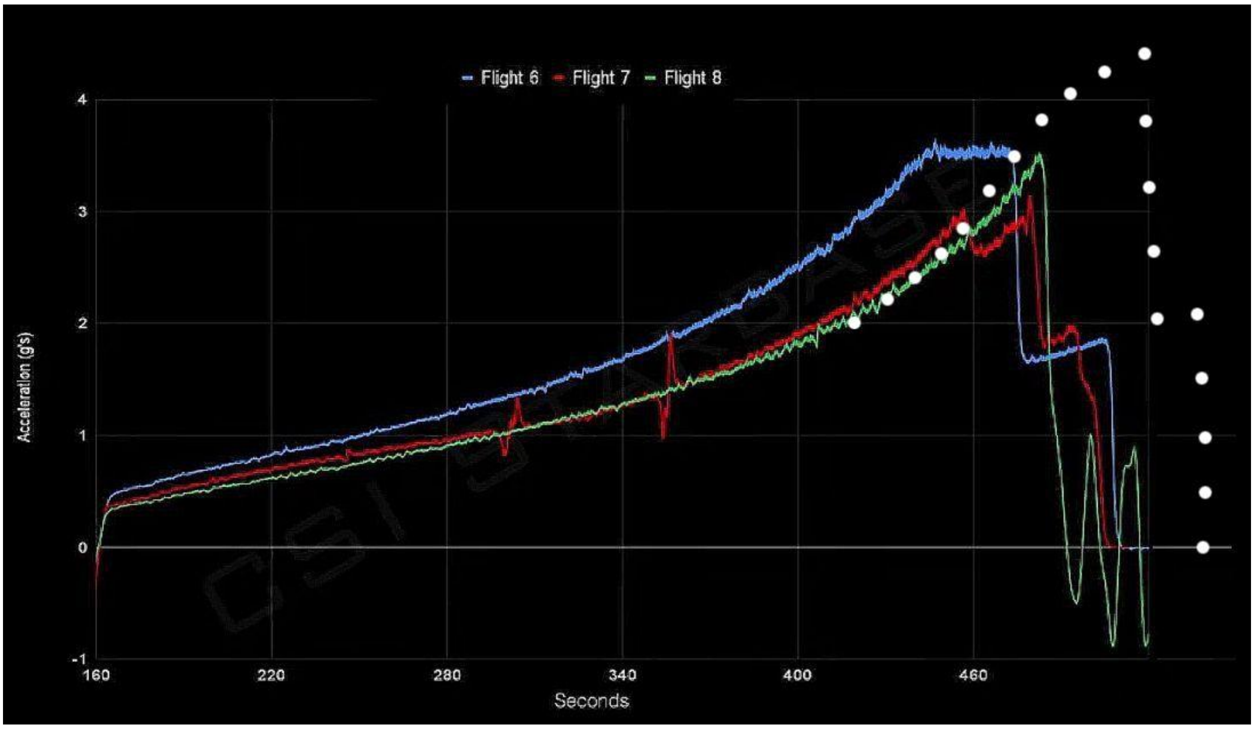

Fig. 2 – Accelerations of Starship second stage (lines) in sixth – eighth flights (IFT-6 – IFT-8), as well as its acceleration in the last, ninth flight (white dots)

The acceleration in boost phase of the second stage in the last, sixth flight of its V1 version is shown by the blue line, red curve refers to the seventh, and green one to the eighth flights (the first and second with V2 version of second stage). As in all launches, starting from the second (in the first, the stages weren't separated), after reaching an acceleration value of 35 m/s^2, the engines were throttled so that the acceleration of the stage would remain constant, apparently for design dynamic loads on the vehicle wouldn't be exceeded. And this acceleration value was maximal along the entire flight trajectory of the second stage (for example, when it was braking in the atmosphere, the acceleration didn't exceed 17 m/s^2). At the same time, as shown in paper [7], the increase in the frequency of hydroacoustic oscillations in the lines supplying fuel components to the engines caused by throttling led to the excitation of auto-oscillations of Pogo type. It was they who caused the explosion of the second stage during the second launch of Starship. After that, during all flights of this second stage version, the side engines began to be switched off early, and a characteristic step appeared on the acceleration graph, clearly visible in Fig. 2 on the sixth flight.

During the first two flights of V2 second stage version, it never managed to exceed this mark, so we don't know how it should have accelerated after reaching this characteristic point. It is clear that own frequency of elastic longitudinal oscillations, which, together with hydroacoustic oscillations frequency, is responsible for Pogo occurrence, changed when transiting to new version of the stage. Without the ability to carry out the appropriate calculations, and in order to reliably avoid Pogo on the methane supply lines, as in the V1 version, SpaceX, as is known, radically redesigned pipelines for feeding it to the external engines of the V2 stage, resulting in the destruction of this structure by transverse oscillations on the seventh flight. At the same time (see red curve in Fig. 2), after the fires that started in the engine compartment, rocket engines began to shut down one after another, which ultimately led to the destruction of the stage as a whole and its combustion in the atmosphere [8]. The fact that the acceleration of new version second stage, all other things being equal, was significantly less than that of the old one, is explained by the fact that it had 300 tons, or 20 % more propellant. However, the lower average acceleration had to be compensated for by a longer acceleration time, what is evident from data of the ninth flight, see Fig. 2.

As a result of more rigid fastening of the pipelines supplying methane to the side engines, the newly emerged problem of lateral vibrations was solved, and these engines worked 7 – 8 seconds longer in the eighth flight, giving the stage that same acceleration of 35 m/s^2 [8]. And as was already written above, at this point the engines began to shut down again (see green curve in Fig. 2). Even a slight decrease in thrust compared to the previous flight in the final section of the acceleration trajectory didn't help. And if before the ninth flight there could still be some doubts about the reasons for these failures, then after it there were no more doubts. It is enough to look at the change in the engine operating mode in the last flight compared to the penultimate one. In the eighth minute of the flight, white dots characterizing the acceleration curve at IFT-9 lie on the curve corresponding to IFT-8 with a good degree of accuracy. At the same time, the mass of the second stage in the ninth flight, if it differed from its mass in the eighth flight, at least due to four additional Starlink satellite mockups, then not by much. So the engines in these flights worked in the same or almost the same modes.

But by the 456th second of the flight, by the time of the first external engine failure in the seventh flight (according to the video [9]), one can already notice an increase in acceleration, and, respectively, engines thrust in the ninth flight compared to the eighth. And by the 503rd second, the moment of emergency shutdown of the first external engine in the eighth flight, the excess thrust is already at least 10 – 12 %. And then the thrust grows further, increasing acceleration, regardless of any structural limitations to ~ 43 m/s^2, exceeding the previous maximum level by 20 – 25 % (see Fig. 2). Table 1 show the accelerations of all three V2 version second stages at the moments when they reach the maximal values of this parameter.

Table 1 – Maximal accelerations achieved in 7 – 9 flights of Starship second stages

Flights	**Flight time (s)**		
	456	503	519
	Acceleration (m/s^2)		
Seventh	30	–	–
Eighth	27	35	–
Ninth	27.5	39	43

During acceleration, mass of the stage gradually decreases due to fuel exhaustion, and the frequency of its own elastic longitudinal oscillations gradually increases. While the engine thrust is constant, the frequency of hydroacoustic oscillations in the fuel and/or in oxidizer supply lines is also constant. If (taking into account the multiplicity) the elastic frequency is somewhat lower than the hydroacoustic frequency, then a moment may come when the difference between them is so small that Pogo occurs. And this is exactly how, judging by the available data, V2 version of the second stage entered this dangerous mode in the eighth flight at about the 500th second of acceleration.

While in the ninth flight, rapid increase in engine thrust, accompanied by a corresponding drop in the frequency of hydroacoustic oscillations, allowed to pass quickly this zone of auto-oscillations occurrence, as it happens all the time, let's say, when starting and reaching the nominal engine mode. Moreover, a similar approach to active suppression of Pogo was first implemented earlier, even during the realisation of Starship first stage boostback in the third to fifth flights. To analyse the application of this technique, we will consider those episodes in more detail, especially since the trajectory data of those manoeuvres were quite available in the required volume and quality.

III. Active suppression of Pogo during boostback by controlling engine thrust

As is known, on November 18, 2023, during Starship second flight, at the first attempt to perform first stage return manoeuvre (boostback), it exploded, see Fig. 3 [10].

Fig. 3 – View of the sky one second after first stage explosion during second flight

However, 4 months later, on March 14, 2024, during the third flight, boostback was completed relatively successfully – stage movement was able to turn, albeit in a slightly different direction than planned, and it exploded already when the engines were turned on at the final phase of braking [10]. That time, such a result was achieved due to active suppression of Pogo by throttling the engines during the boostback. Knowing the frequency of auto-oscillations at which the explosion occurred, and the parameters of the power plant at that moment, and also having by that time the formula for recalculating the frequency of hydroacoustic oscillations based on the pressure drop on pumps, derived by the author of this paper, using one of the methods available to SpaceX, the company's engineers reduced the thrust of the engines during this manoeuvre [11], see Fig. 4.

Comparing acceleration of first stages in the second – 25 m/s^2 (thin gray line) and the third – about 30 m/s^2 (thicker lilac line) flights on the quasi-stationary phase of boostback, highlighted by the rectangular frame in Fig. 4, taking into account that in the second flight only 9 engines out of 13 were working on this part of the trajectory, it is easy to find that in the third flight the thrust per engine was approximately 15 – 20 % lower than in the second. The calculated acceleration in the second flight with all engines working should have been about 36 m/s^2. Its level is shown in Fig. 4 by three blue dots. It was this mode that unexpectedly for Starship's designers turned out to be inside Pogo excitation zone due to oscillations in oxygen supply system to the engines of first stage inner ring.

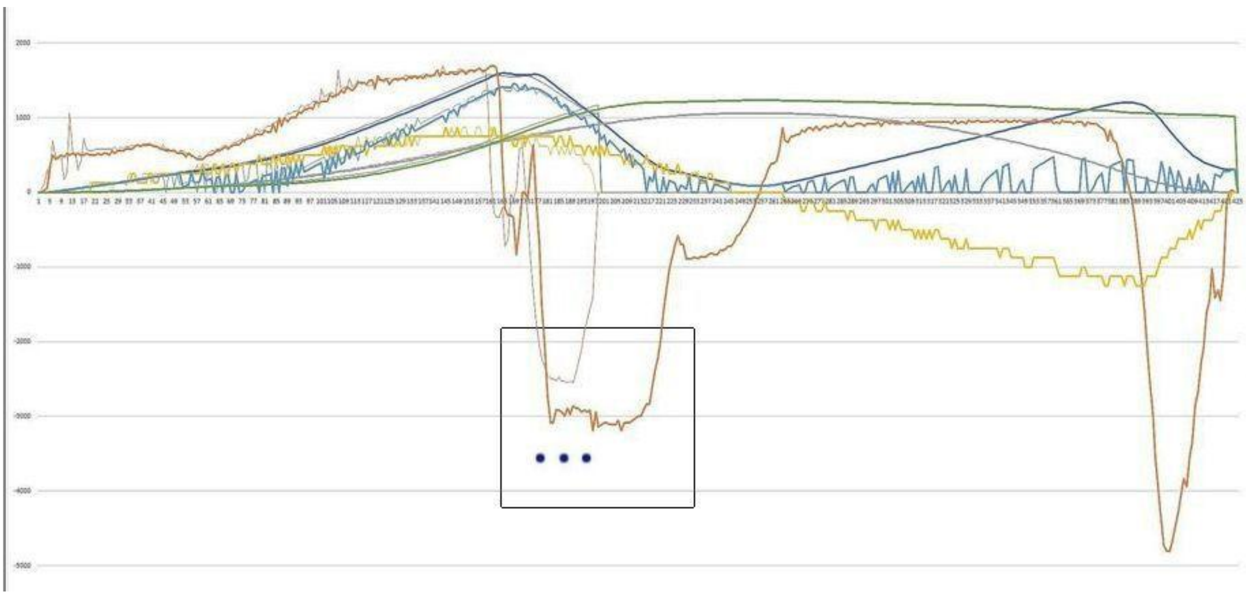

Fig. 4 – Acceleration, speed, altitude, and straight (horizontal) range, as well as horizontal and vertical components of Starship booster velocity during second and third flights [12]

The indicated reduction in thrust, which in the third flight led to an acceleration during boostback of ~ 30 m/s^2 during the operation of all 13 engines, didn’t completely eliminate the excitation of auto-oscillations, since at the very end of the boostback they still reached such a level that the engines of the inner ring began to spontaneously and asymmetrically switch off [13], see Fig. 5.

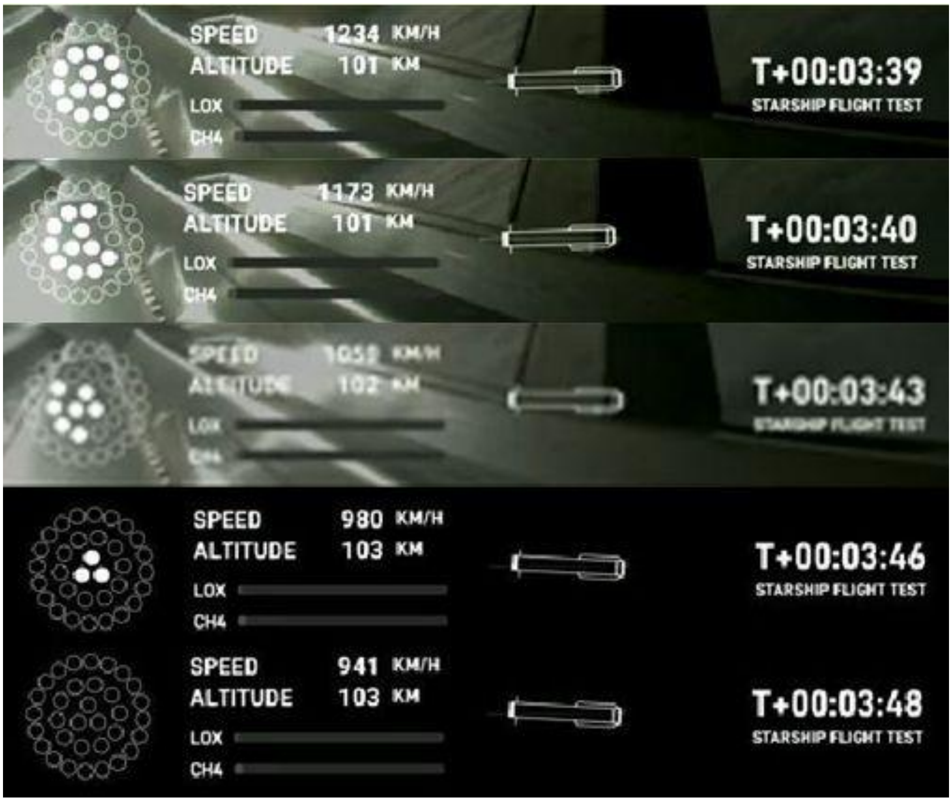

Fig. 5 – Spontaneous shutdown of first stage inner ring engines at the end of boostback in the third flight

As can be seen from Fig. 5, the engines of first stage inner ring were switched off within approximately 7 s, starting from one side of the ring. Obviously, such a switching off order was caused by the asymmetrical arrangement of liquid oxygen mirror in the tank relative to its central axis. On one side of the tank, the layer of oxygen remaining there, under the action of the almost orthogonal inertia and gravity forces, was higher than on the other. Therefore, its hydrostatic pressure also differed, which led to comparatively small but significant differences in the pressure at the inlet to the engine pumps, and this, in turn, affected the pressure drop on the pumps. The higher the drop, the lower the frequency of hydroacoustic oscillations, the sooner the frequency of elastic oscillations can approach this frequency, and the sooner the fuel system of a given engine will begin to generate auto-oscillations, leading to its switching off.

Therefore, the engine or, more precisely, their near couple, see Fig. 5 at T+00:03:40, with minimum oxygen layer thickness above the pipeline inlets, was the first to shut down. And then, as the oxygen was consumed, the shutdown front began to move along the ring together with a decrease in oxygen level symmetrically relative to the axis passing through minimum and maximum points of this level in the tank, until all the engines of this inner ring were successively shut down. Thus, the upper engines of the ring were the first to shut down, which led to the "upward dive of the stage" noticeable even in Fig. 5 and a steeper return trajectory. Having worked for 2 – 3 s after the shutdown of the last engines of the inner ring, 3 central swinging engines were able to prevent uncontrolled rotation of the booster, however, they were no longer able to completely bring the magnitude and direction of the velocity vector after the cut-off to the specified value, and the booster attempted to splash down with an explosion at off-settlement point, further from coastline than planned [11].

With the improved data, SpaceX was finally able to completely eliminate the impact of boostback oscillations on Starship first stage flight on June 6, 2024, during the fourth flight. Figure 6 shows a comparison of flight parameters for the third and fourth launches [14].

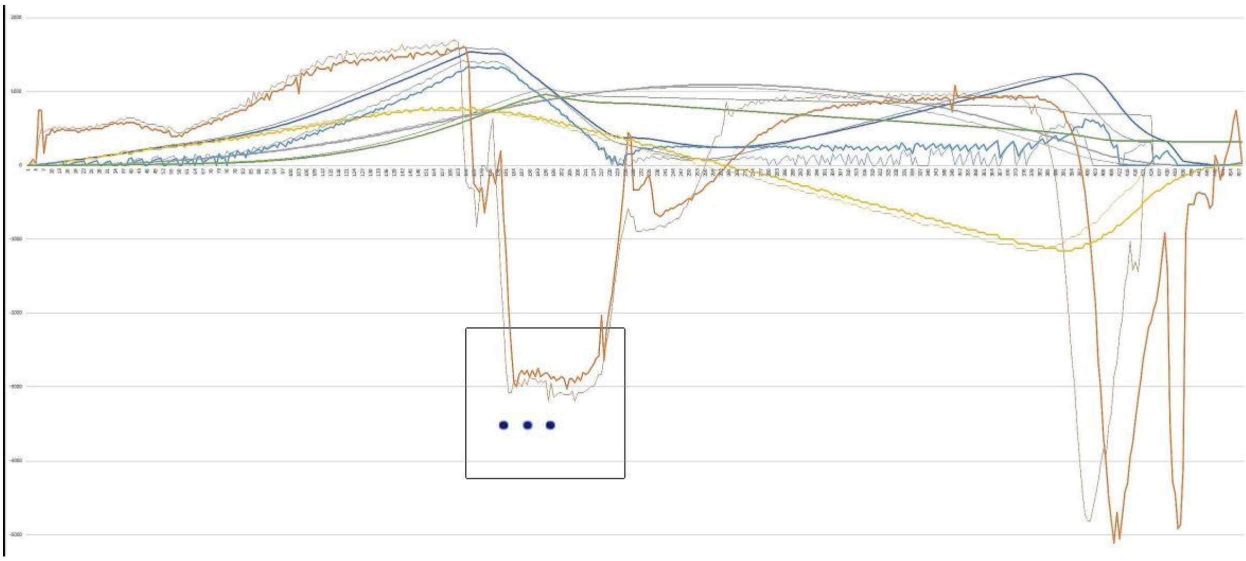

Fig. 6 – Acceleration, speed, altitude, and straight (horizontal) range, as well as horizontal and vertical components of Starship booster velocity in the third and fourth flights

Although the differences between the thrust levels in these two flights in quasi-stationary boostback modes are minimal (see the area in Fig. 6 highlighted by the rectangle), the consequences of this change in the rocket engines operating algorithm turned out to be quite significant.

It turned out that it was enough to reduce the maximum thrust of the engines by approximately 3 % more, bringing the maximum (by module) acceleration during boostback to ~ 29 m/s^2, to completely suppress Pogo and ensure ideal axisymmetric program shutdown of the inner ring engines, see Fig. 7 [15]. Initially, first 5 engines of the ring were switched off simultaneously, every other one, and then the remaining 5. After 8 s, 3 central engines were also switched off simultaneously. And then, the booster made a planned flight and smoothly splashed down at the planned point in the Gulf of Mexico. True, it then exploded, but this was a natural development of events associated with its horizontal position on the surface of the water. The next booster, picked up by the launch and landing complex after fifth flight, remained practically intact.

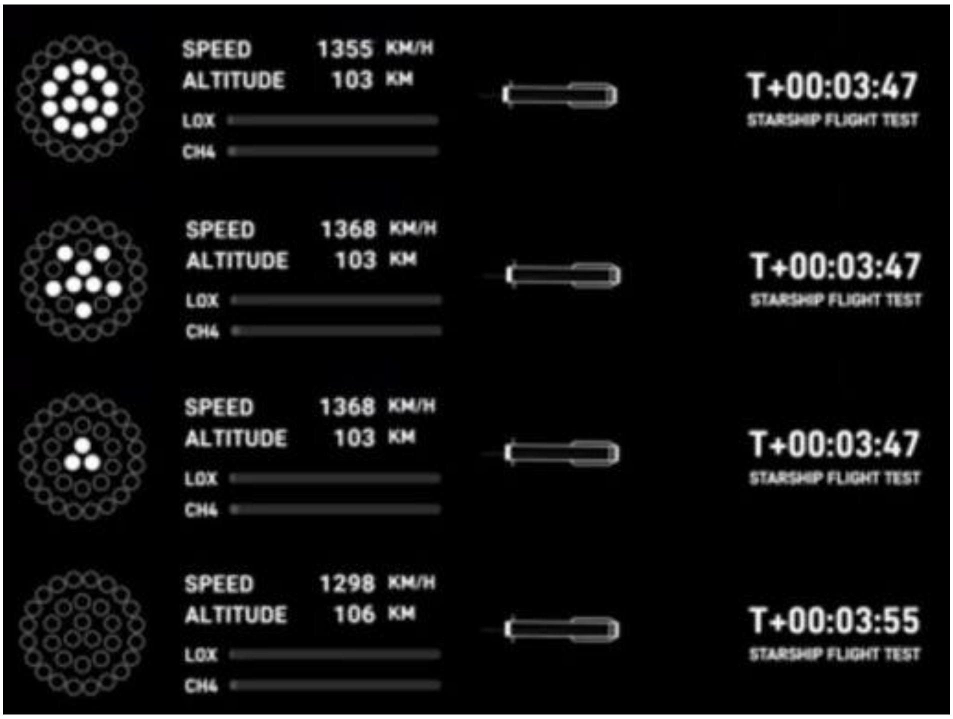

Fig. 7 – Planned axisymmetric shutdown of the first stage inner ring engines upon completion of the boostback in the fourth flight

However, the improvement of the engine control algorithm during boostback didn't end there. The required manoeuvre was possible only by increasing the frequency of hydroacoustic oscillations by ~ 10 % and, accordingly, reducing the thrust of the power plant by ~ 20 % of the originally planned level, which, naturally, led to an increase in losses of the characteristic velocity. Therefore, in the fifth flight on October 13, 2023, when the first stage was first picked up by the launch and landing complex, the maximum acceleration and, consequently, the engine thrust increased during boostback by about 1.5 times (acceleration – from 29 to 43 m/s^2), see Fig. 8. At the same time, the entire flight of the first stage was completely successful and faster than before. Pogo process didn't occur because the frequency zone where it could exist was quickly passed, and it didn't have time to fully evolve where it would have been possible in the quasi-stationary flight mode.

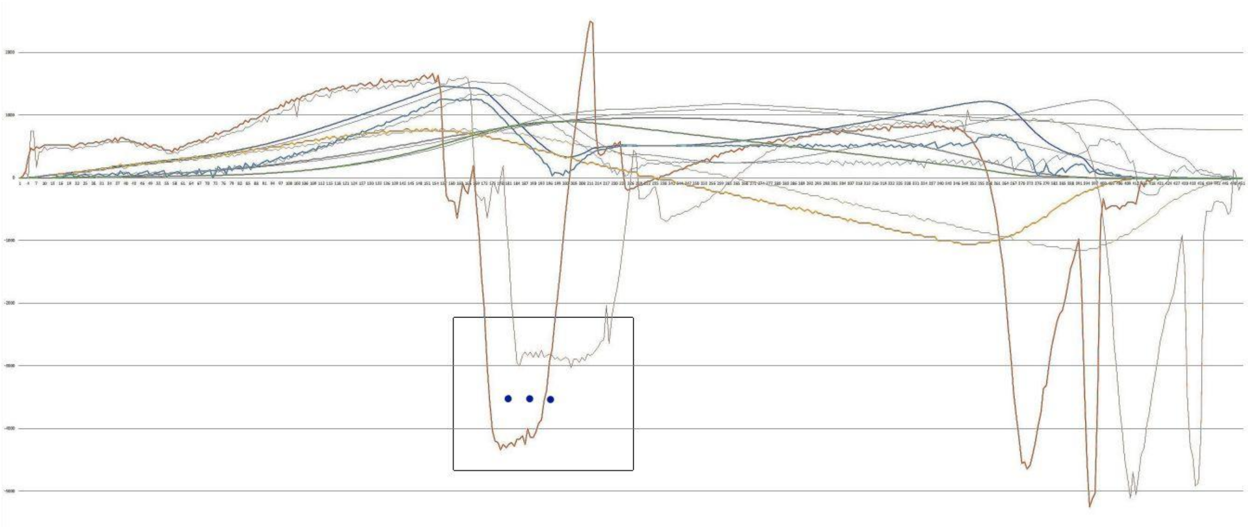

Fig. 8 – Acceleration, speed, altitude, and straight (horizontal) range, as well as horizontal and vertical components of Starship booster velocity on the fourth and fifth flights [16]

Thus, comparing the development of Pogo processes detection and suppression during boostbacks in the second to fifth flights, and at the finish of V2 version second stage in the eighth and ninth flights, we can see a complete qualitative similarity between them: first, the explosions of the stages due to Pogo, and then in the following flights – an increase in the thrust of the power plant to "skip" from the dangerous mode. The purpose of thrust control was a rapid decrease in the frequency of hydroacoustic oscillations so that the moment, during which they turn out to be close (taking into account the multiplicity) to the frequencies of own elastic longitudinal oscillations, would be as short as possible. When this was done for the first time, Pogo suppression occurred first through successive reductions in thrust, and the process took 4 flights to work out. And the second time there were no intermediate stages, and the destruction of the second stage on the eighth flight due to Pogo in the oxygen supply lines to the side engines was eliminated by reducing the frequency of hydroacoustic oscillations already on the next, ninth flight.

However, although Lord God, as A. Einstein suggested, "is not malicious", however, he laughed again at the efforts of SpaceX company in the fight against Pogo and showed at the end of second stage acceleration in the ninth flight another version of it already on the central engines in the oxygen supply lines to them, the length of which was slightly different, and therefore Pogo process arose there a little later. Although it didn't have time to evaluate significantly, and there were no explosions of engines this time, it was still enough to destroy this vehicle.

IV. This has never happened before, and here it is again

After the ninth flight, when the maximum thrust of Raptor-2 engines of the second stage was increased, which made it possible to ensure the operation of their version with a vacuum nozzle, at least until the time of ~ 520 s from the launch, at the cost of increasing maximum overload of the stage by 20 – 25 % compared to all previous flights, for the first time there was a non-simultaneous shutdown of three central engines of the stage, see Fig. 9 [1].

Fig. 9 – Non-simultaneous shutdown of three central engines of the second stage during the ninth flight

The most probable, if not to say obvious, systemic explanation (if we don't consider random failures of some elements of one of these engines) is the excitation of auto-oscillations on one of the three such engines. Qualitatively, the description of this process is completely analogous to the spontaneous shutdown of those inner ring engines from first stage in the third flight during a boostback due to Pogo. And the quantitative differences are explained by the rather large distance from each other of those ten inner ring engines and the proximity of these three central engines. Further explanations of this phenomenon are hardly required.

As a result of the premature shutdown of at least one of the three central engines, a moment of force was created, due to which the stage began to rotate uncontrollably. As follows from the subsequent frames of this flight video, with the help of the gas rudders it was possible to almost completely stop this rotation, but in doing so the boost gas was spent, and further control of the stage's orientation was lost [1].

Fig. 10 – Gas leakage through the side wall of Starship second stage after its engines are cut off

In addition, the maximal stage overload at the end of the acceleration of about 4.3 – 4.4 instead of ~ 3.5 units in all previous flights could have led to failures and/or destruction of some structural elements of the second stage. At least for 40 seconds from 9:30 to 10:10, it was possible to observe the outflow of blue gas (most likely, boost gas, consisting almost entirely of oxygen) through the side wall of the stage (no valves were provided there), see Fig. 10 [1].

This gas emission, apparently through a crack in the wall, on the one hand increased the stage's spin, and on the other hand reduced the reserves of boost gas for controlling its orientation. As a result, as in the third flight, the second stage entered the atmosphere in an unplanned manner and was destroyed, for the third time in a row not allowing for an experimental assessment and analysis of innovations related to improving its aerodynamic configuration and thermal protection, which SpaceX began working on immediately after the completion of the fourth flight, which was already a year ago [17, 18]. But all this might not have happened if SpaceX had used the equations for calculating the frequency of hydroacoustic oscillations to predict the conditions for the occurrence of Pogo when changing the design of Starship, and not had applied only the consequences of their decisions only after accidents had already occurred.

Conclusions

1. The explosion of second stage in the ninth flight at the end of three side engines with vacuum nozzles operation, as happened in the eighth flight, didn't occur because all its engines in this period, right up until their shutdown, worked at a thrust level 15 – 20 % higher than before. In this regard, the absolute maximum of the stage overload was equal to 4.3 – 4.4 compared to no more than ~ 3.5 units in all previous flights.
2. A rapid increase in thrust at the finish with a corresponding decrease in the frequency of hydroacoustic oscillations made it possible to pass Pogo excitation zone with hydroacoustic oscillations on the liquid oxygen supply lines of these side engines, completely analogous to how this was first done in the fifth flight during first stage boostback.
3. However, during the subsequent shutdown of three central engines with conventional nozzles, one of them, due to the onset of Pogo, was shut down a fraction of a second earlier than the other two, which caused the stage to rotate uncontrollably. This happened similarly to what happened on the third flight during the boostback with inner ring engines of first stage.
4. Furthermore, for at least several tens of seconds, there was a lateral leak of gas through the wall of hull where no valves or openings were visible. This also contributed to further stage spin, and at the same time reduced the amount of boost gas available to the attitude control system.
5. As a result, the second stage entered the atmosphere in an unexpected manner and was destroyed for the third time in a row.
6. This didn't allow achieving the main goal of the ninth flight – to test new thermal protection solutions, without which further progress of Starship project is impossible.

7. Thus, this project is being developed in a reactive mode, without any attempt to foresee problems occurrence during testing in advance, despite the possibilities available to do so. It is obvious that the entire responsibility for the unfavorable development of Starship project lies with the top management of SpaceX.

Links

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2. Video. *SpaceX*, March 6, 2025 // https://www.spacex.com/launches/mission/?missionId=starship-flight-8
3. Starship’s Ninth Flight Test, *SpaceX*, May 27, 2025 // https://www.spacex.com/launches/mission/?missionId=starship-flight-9
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13. Replay! SpaceX Starship launches on 3rd integrated test flight. *VideoFromSpace* 14.03.2024 // https://www.youtube.com/watch?v=Dr8ZaMAa5jw
14. OneSpeed – Re: Starship Flight 4 UPDATES: Starbase TX: 6 June 2024, Reply #203. *NSF*, 06 June 2024 // https://forum.nasaspaceflight.com/index.php?topic=60929.msg2598941#msg2598941
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17. R. Weber – Starship flight 4 milestones effect changes to flight 5’ Ship. *NSF*, 12 June 2025 // https://www.nasaspaceflight.com/2024/06/starship-flight-4 -milestones-flight-5/
18. It’s About Damn Time: Starship's Upgraded Flaps & Nosecone. *Ringwatchers*, December 23, 2024 // https://ringwatchers.com/de/article/s33-nose

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