Analysis of Starship booster design and its evolution over 2.5 years of flight testing

Yu. I. Lobanovsky

He who looks from the outside sees with eight eyes.
Go players' proverb

Summary

This work shows that completed by the end of 2025 phases of development programs for two most promising missile systems – Starship and New Glenn, as well as the accident on November 21, 2025, during cryogenic testing of Starship booster latest V3 version, allowed for an analysis of Starship fundamental design features. It follows from this analysis that the seemingly inexplicable increase in the cross-section of pipeline supplying methane to the engines in V3 version is caused by problems with sustainability of its supply during rapid rotation of the booster around its transverse axis during boostback maneuver.

This led to displacement of oxygen header tank for engines used during landing (i.e., capture of booster by landing tower) from the center to main tank side wall, resulting in at least 7 different lengths for pipelines supplying oxygen to the engines which operates during landing. This, in turn, means that there are opportunities for up to 7 new variants of Pogo auto-oscillations to occur, which could lead to a booster disaster during landing. Moreover, Pogo have already caused 6 accidents in 11 test flights, and results of testing Starship first two versions allow to expect that suppressing such a large number of new variants of Pogo using SpaceX flight testing method may simply be physically impossible.

… This part of the summary, concerning the solution to oxygen header tank problem of Starship booster, is currently closed to the public.

And an assessment of all the design solutions used in the development of the latest booster version approve that full-fledged control over Starship program has essentially been lost.

Ключевые слова: *Starship, New Glenn, пого, авария, прототип, труба-бак, напорный бак*

Keywords: *Starship, New Glenn, Pogo, accident, prototype, pipe-tank, header tank*

I. Introduction

Currently, by the end of 2025, important phases in the development of two most advanced programs for creating promising rocket systems – Starship and New Glenn, of SpaceX and Blue Origin respectively – have been completed almost simultaneously (with an interval of exactly one month). Despite the fact that first of these, more ambitious and innovative Starship system, has already completed 11 flights into near-Earth space during two phases of full-scale testing, it is still far from solving even the most initial task – launching a payload of about of 100 tons into low Earth orbit and successfully returning both its stages to Earth afterwards. Moreover, as will be shown later in this work, permanent changes to its design in a challenge-response mode, that is, in an agile technology style, while perhaps justified in solving local problems that don't yet have sufficient scientific justification, can lead the entire project to a dead end when making global design decisions, from which there will be no way out. In addition, some of the most important aspects of this project are being concealed by management of SpaceX not only from the outside world, but, as will be seen later in this work, apparently also from their own engineers designing various subsystems of this reusable rocket system, which sometimes leads to completely anecdotal incidents.

Meanwhile, another rocket system – New Glenn, which is also quite large and innovative, but generally occupies an intermediate position between Starship and launch vehicles of recent past in terms of these characteristics, essentially completed testing in its second flight, launching two Martian spacecraft into a trajectory towards the L_2 Lagrange point of the Sun-Earth system. Its first stage successfully landed on a floating platform [1]. This provides an opportunity to compare the engineering solutions used in the design of these two rocket systems, and also, by drawing on information about the even lighter and highly successful partially reusable Falcon 9 launch vehicle from SpaceX, to try to understand the genesis of some fundamental features of Starship design and the reasons for its changes from version to version, and to assess what they might ultimately lead to.

II. Main results of Starship first two versions (V1 and V2) flight tests

Can anything good come out of Nazareth?
John 1:46

Broadly speaking, the course of the two previous test phases of two Starship versions, V1 and V2, was determined by actions aimed at solving two key problems: identifying and suppressing Pogo auto-oscillations, which constantly arose in various forms in this system, and creating acceptable thermal protection for second stage (Ship). However, Pogo problem, which unexpectedly arose from the very first seconds of first flight [2], when the problems with thermal protection were still a long way off, was completely was kept silent by SpaceX management and continues to be kept silent to this day. Measures to suppress this destructive auto-oscillation process were initially presented as something else [3]. Then, when before third flight (in March 2024), they received "good news" from cold Russia [4], which partially (but far from completely) opened their eyes to this phenomenon, they enthusiastically began to suppress Pogo by changing the engine operating modes, without reporting anything to anyone or explaining anything.

In just 11 flights, SpaceX encountered at least 8 instances of Pogo. The catastrophic auto-oscillations detected during the first flight were suppressed by introducing a special insert between the rocket stages – an intermediate compartment. In all subsequent flights, starting with the third, the thrust of the engines was programmatically reduced four times and increased three times at previously problematic phases of the trajectory to decouple the frequencies of elastic longitudinal vibrations of the hull and hydroacoustic oscillations in the fuel system [5, 6]. And in the seventh flight, an explosion of the second stage occurred due to transverse oscillations and the rupture of at least one of three long, thin, and unsupported pipelines of new design for supplying methane to the engines of its second stage. This was done on the first instance of second stage V2 version, in order to, lacking the ability to calculate the impact of their own actions on Pogo oscillations due to changes in the fuel system geometry resulting from the lengthening of V2 version stage, to cancel the previously implemented programmatic thrust reductions at the end of its acceleration phase, which reduced payload mass. Thus, even the explosion in the seventh flight although not a direct result of Pogo, but it was an indirect consequence of this process influence on the stage's design.

Ultimately, the first three launches of each Starship version, in one way or another, ended in accidents due to Pogo, in two launches even twice, and only three flights of the first version and two of the second could be productively used to test spacecraft heat shield. In this area, quite encouraging results have been achieved, but even here, there is still a long way to go to the finish, whatever it may be, and if Pogo occur again unexpectedly and unpredictably along the way, movement along it could come to a complete standstill.

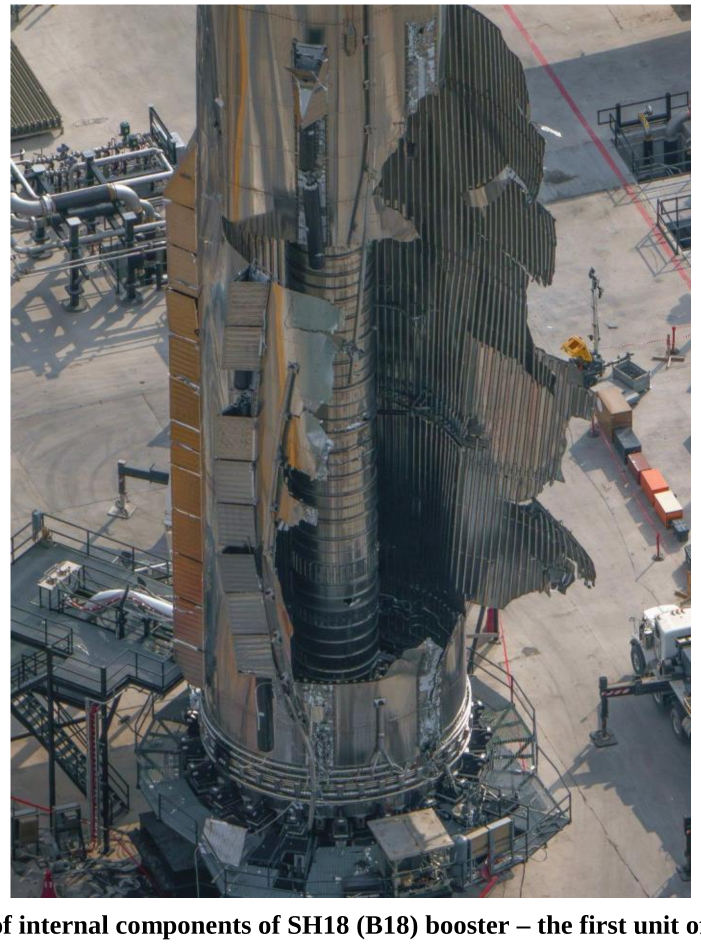

Fig. 1 – General view of internal components of SH18 (B18) booster – the first unit of new V3 version after unsuccessful cryogenic testing [7]

At the same time, SpaceX, at the first opportunity, sought to replace engine throttling, performed to suppress Pogo, with engine forcing, to "skip" through the dangerous mode and avoid losing payload mass due to reduced thrust. And it is this aspiration that explains the changes in the design of V3 booster compared to V1 booster (V2 version was never created), which external observers were able to see after first instance (SH18 or B18) of new version ruptured during cryogenic testing on November 21, 2025 (see Fig. 1). This event occurred just 8 days after the second, successful flight of New Glenn rocket, and it is their joint consideration that allowed for quite definite conclusions about principles of construction and development paths of Starship booster design.

A comparison of diameters of central pipes for supplying methane to the engines of V3 and V1 versions of the booster (see Figures 1 and 2) reveals, at first glance, an inexplicable increase in its cross-section in the new version.

What for? The larger the cross-section, the greater the mass of the pipe, and yet there is a constant effort to reduce the overall mass of the rocket structure. It will be shown later how understanding these changes, in conjunction with an analysis of New Glenn launch vehicle design, proved to be the crystallization point from which the overall analysis of Starship booster design, conducted in the subsequent sections of this article, emerged.

Fig. 2 – Render of oxygen tank lower part of SH7+ booster, version V1, with the lower section of central pipe for methane supply [8]

Comparing Figs. 1 and 2 reveals that the central methane supply pipe of V3 booster has increased in volume several times and has become absolutely enormous – its diameter is now almost the same as that of entire Falcon 9 rocket. This is hardly a merit, as it increases complexity and mass of the booster fuel system.

III. Why has cross-section of central methane supply pipe to booster engines increased so dramatically?

We wanted the best, but it turned out as always.
V. S. Chernomyrdin

It is claimed that in this configuration, the central methane supply pipe to the booster engines, with its significantly increased cross-section, also serves as an intermediate header tank, and that this is a very successful solution [9]. However, it is quite obvious that by increasing the height of methane tank while correspondingly decreasing the height of oxygen tank, while maintaining its volume through a thinner central pipe with normal throughput, we would obtain a lighter structure. And all this has already been implemented in version V1 of the booster, see Fig. 3.

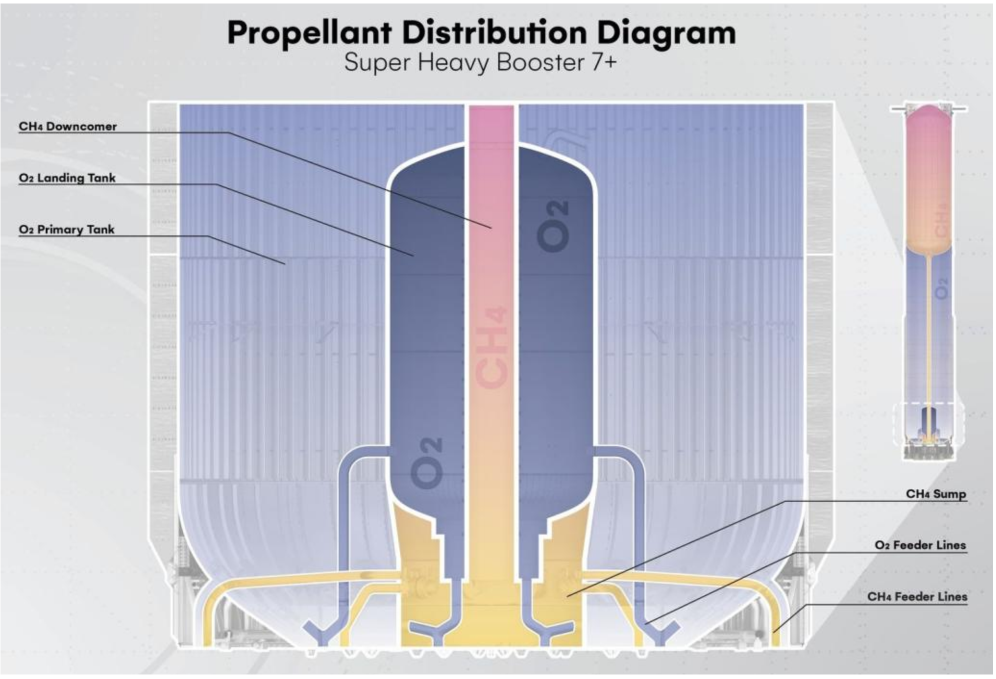

Fig. 3 – Schematic diagram of SH7+ booster, version V1, fuel distribution system [8]

The oxygen landing header tank, with its symmetrically arranged oxygen supply pipes, is well integrated around the relatively thin central methane supply pipe to the engines (see Fig. 3 and 4).

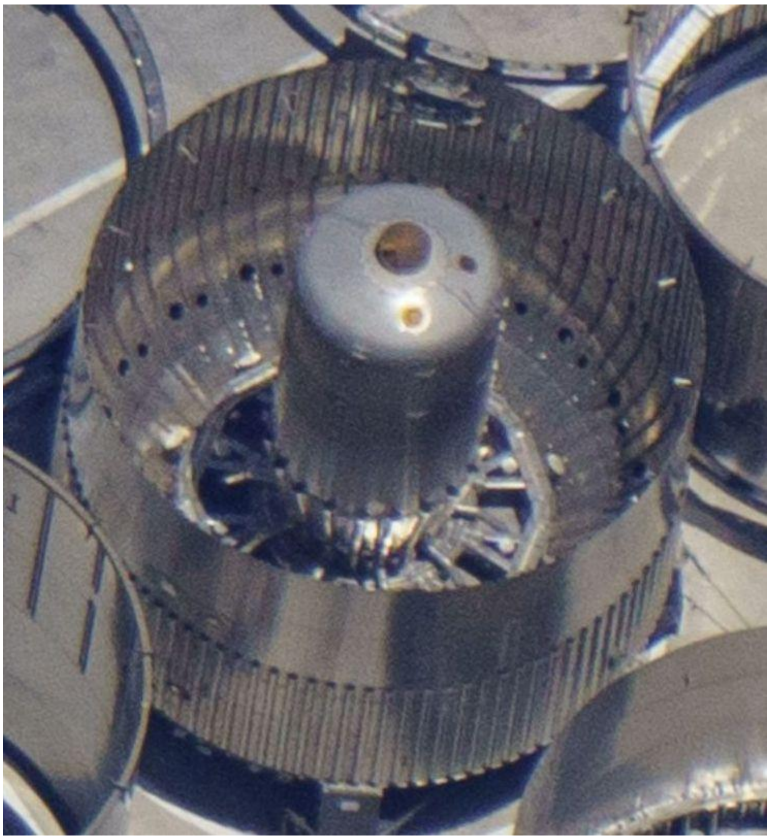

Fig. 4 – Lower part of SH7+ booster, version V1, main oxygen tank, with central landing oxygen tank [8]

However, on new V3 version of booster, due to the enormous central pipe for supplying methane, it is no longer possible to place the oxygen landing tank in the center of main oxygen tank. Therefore, it is shifted to the side, distorting the previously symmetrical structure (see Fig. 5).

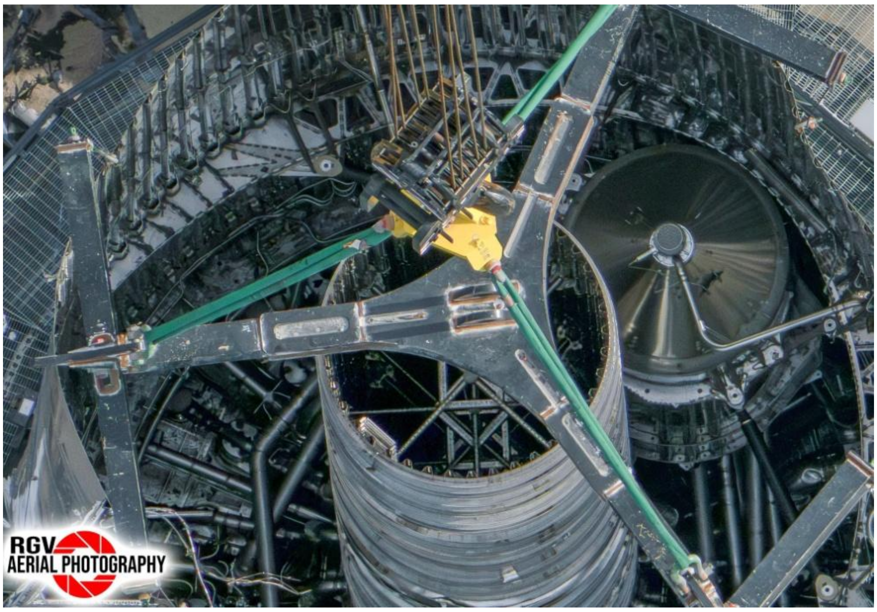

Fig. 5 – Lower part of SH18 booster, version V3, main oxygen tank with a side oxygen landing tank [9]

But worst of all, with this arrangement of the oxygen landing tank, 13 pipes supplying oxygen to 13 engines operating during landing will inevitably have at least 7 different lengths instead of the previous two (see Fig. 6). This means that there is a possibility of up to 7 different Pogo variants occurring, which may be simply impossible to resolve through flight testing. According to the chosen method for identifying Pogo, testing this single component alone could require up to 7 Starship flights with explosions near landing tower.

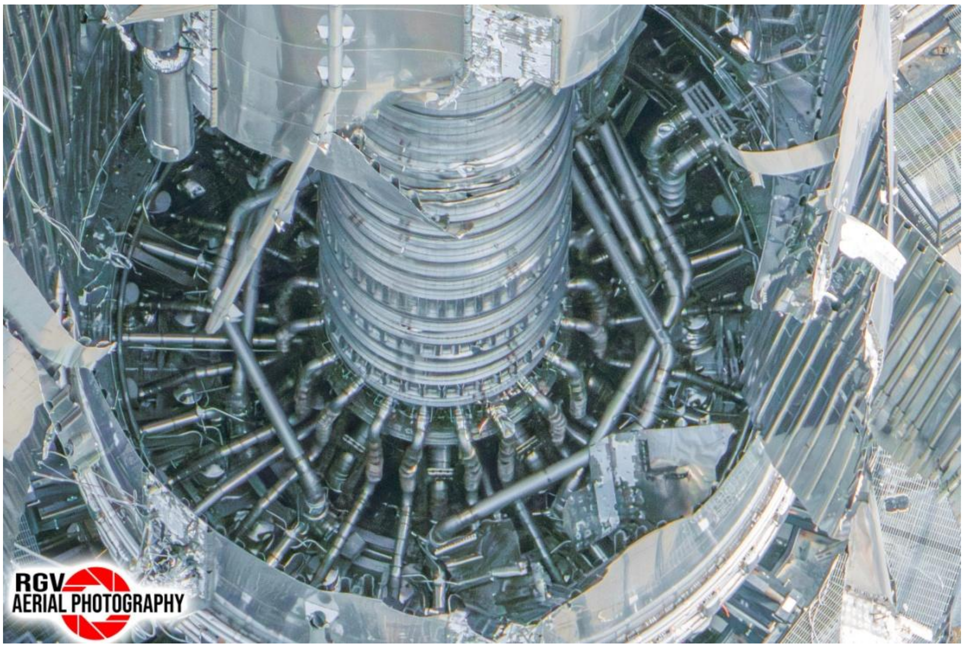

Fig. 6 – Visible part of pipelines running from the side oxygen landing tank to the engines of SH18 booster, version V3 [7]

What caused such a clearly fuel distribution system unbalanced architecture of SH18 booster version V3 to emerge from the quite logical architecture of the previous version? Surprisingly, it was due to the fight against Pogo. The most dynamically complex maneuver performed by Starship booster is boostback – a 180° rotation around its transverse axis after hot staging, with 3 central engines operating and 10 inner-ring engines igniting during this rotation. The second flight demonstrated that it was precisely at this moment, with the initially chosen engine operating mode, that Pogo occurred on the booster, leading to explosion that shattered the booster into small pieces [6, 10]. Recalculating the frequency of hydroacoustic oscillations using a formula obtained by SpaceX from a Russian paper, and reducing engine thrust to exit "Pogo zone," allowed third flight to pass this phase of flight without an explosion (see Fig. 7).

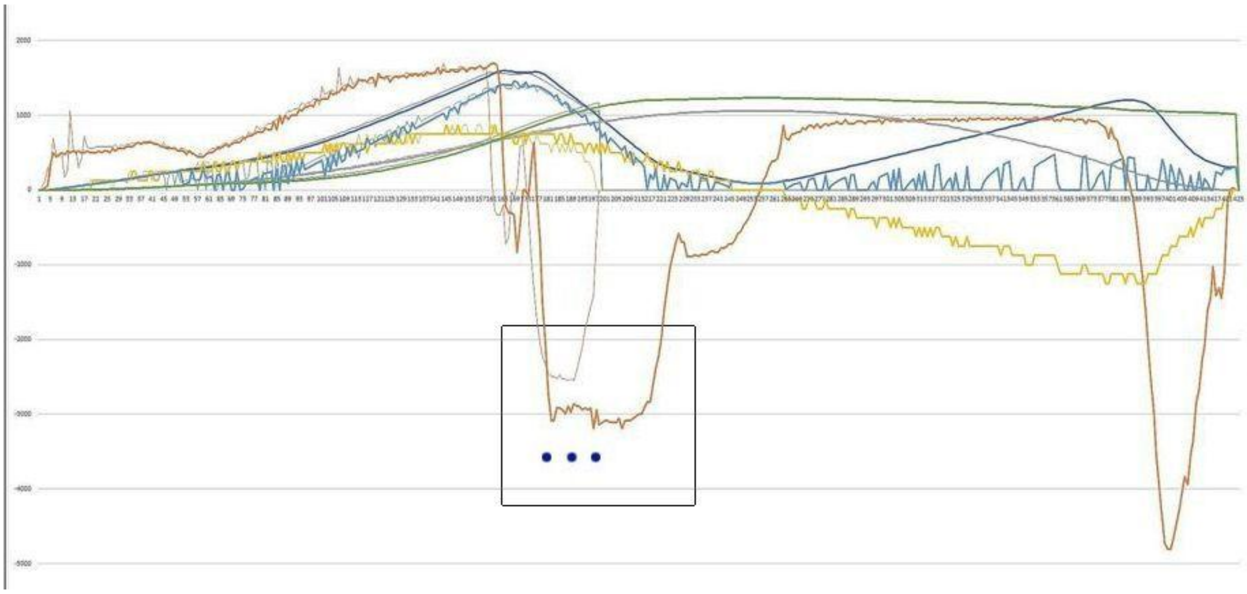

Fig. 7 – Acceleration, velocity, altitude, and horizontal range, as well as the horizontal and vertical velocity components of Starship booster's during the second and third flights [6]

Comparing the accelerations of boosters in the second flight – 25 m/s² (thin gray line) and in the third flight – approximately 30 m/s² (thicker lilac line) during the quasi-stationary boostback phase, highlighted by rectangular frame in Fig. 7, and taking into account that in the second flight only 9 out of 13 engines were operating in this part of the trajectory, it is easy to see that in the third flight the thrust per engine was approximately 20 % lower than in the second. The calculated acceleration in the second flight with all engines operating should have been about 36 m/s². This level is shown in Fig. 7 by three blue dots. This is the mode, unexpectedly for Starship system developers, turned out to be within Pogo excitation zone in the oxygen supply system to the inner ring engines of booster.

Booster explosion during the boostback of the third flight was avoided; however, the reduction in engine thrust proved insufficient, and auto-oscillations still occurred in the third flight, albeit in a relatively weak form, at the very end of this flight phase. This led to a deviation in final velocity vector position after engine shutdown and the booster following an unplanned trajectory [6]. In the subsequent, fourth flight, the engine thrust was reduced by another 3 %, so that maximum acceleration of the booster (thin gray line inside the rectangle) became approximately equal to 29 m/s², see Fig. 8:

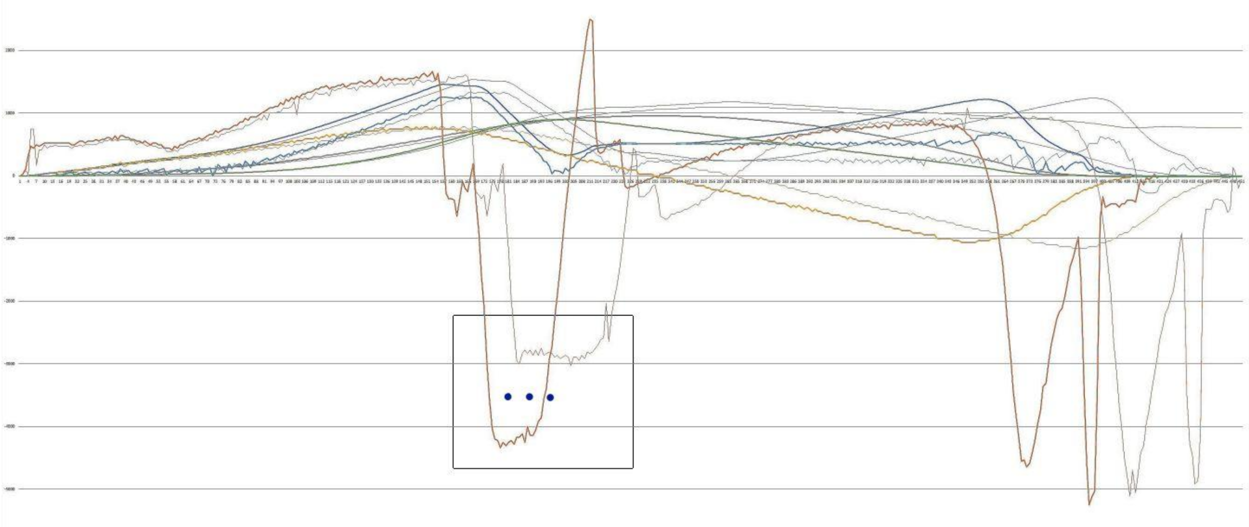

Fig. 8 – Acceleration, velocity, altitude, and horizontal range, as well as the horizontal and vertical velocity components of Starship booster's during the fourth and fifth flights [6]

This time everything went according to plan, and it was the first flight without explosions or major destruction, with both stages successfully performing a smooth splashdown, although the second stage was severely burned, even to the point of having holes in it. However, in the next flight, boostback was performed with a thrust level that exceeded the dangerous level by as much as it was below it in the fourth flight (acceleration increased from 29 to 43 m/s²), see on Fig. 8 at thin gray and thick lilac lines inside the rectangle. The maneuver time was correspondingly reduced. And since then, the same accelerated boostback maneuver was always planned, at least this can be stated up to the eighth launch, after which the presentation of this data was discontinued.

Everything would be fine if it weren't for one circumstance – unlike most first stages of rockets (for example, Saturn V and Falcon 9), Starship booster has heavy oxidizer tank located behind the lighter fuel tank, next to the propulsion system (the N1 and New Glenn rockets have the same design). It's clear that placing the center of inertia as close to the nose as possible is beneficial for the trajectory stability and controllability of a disposable rocket, but for reusable stages, stability is apparently more important during the final, return phase of trajectory, when it is flying in a reversed position. It seems that this consideration led to the choice of this tanks arrangement on the first stage of Starship and New Glenn rockets (in the case of N1, this choice was dictated purely by geometric reasons).

However, this design for Starship booster, combined with pursuit in the second year of flights on maximizing the rotation during the boostback maneuver, led to a new, unexpected problem that was addressed in version V3 of this rocket system. Because of this tank arrangement, the lower part of the methane tank and the propulsion system are located on opposite sides of the stage's center of inertia. During rotation, the centrifugal acceleration is directed upwards from the bottom of this tank, counteracting force pressing the fuel against it. In addition, some of the engines in the inner ring are also subjected to tangential acceleration from the booster's rotation. During a forced boostback, the total "lifting" acceleration is estimated to be at least 15 m/s², which exceeds the initial longitudinal "lowering and pressing" acceleration from operation of only the three central engines (~10 m/s²). Therefore, boostback dynamics are complex, and the small amount of methane stored in the distribution manifold at the bottom of the oxygen tank (see Fig. 3) may not be sufficient for all the inner ring engines to reach operating mode and achieve thereby stable fuel supply to all 13 engines operating during boostback. Apparently, incident in the seventh flight, where one of the inner ring engines shut down and then restarted during landing, may have been related to this effect. Therefore, it is likely that the decision was made to sharply increase the diameter of the methane supply pipeline so that a sufficient amount of fuel would be stored in its lower part, acting as a special header tank, on the opposite side of the center of inertia and near the engines during any rotations.

However, as mentioned above, this led to the displacement of the landing oxygen header tank to the side wall of the main tank, and to the appearance of a whole bundle of pipes of different lengths for supplying oxygen to the engines. This can quite reasonably be seen as setting the scene for a highly probable appearance of a small orchestra (a kind of sextet, consisting of a central performer and 6 pairs of side that of), performing hydroacoustic melodies at 7 different frequencies during landing. So, while some SpaceX engineers, sweating profusely, are studying accidents and changing engine operating modes to suppress the identified Pogo variants, others are just as diligently creating conditions for even more of them to arise. What the company's management is doing in the meantime is difficult to say. But, it can be argued, it is already clear that control over Starship program has essentially been lost. And, in general, it all looks very much like Hercules' battle with the multi-headed Lernaean Hydra, but without Hercules' charioteer Iolaus cauterizing the bases of the severed heads of Hydra with burning brands so that new heads would not grow back [11].

None of this would have been necessary if the propellant tanks had been positioned as usual: the oxidizer in the front, and the fuel in the back, just like on Starship's older sibling, Falcon 9 rocket. Then the bottom ends of both tanks would be located on the same side of the stage's center of inertia as the propulsion system, or, at least, with a small amount of fuel, the bottom of the upper tank would be close to the center of inertia, and the centrifugal acceleration would be small even during sharp turns of the stage. And was the chosen tank arrangement, which ultimately led to the complication and increased mass of the fuel system due to the introduction of a huge pipe combining its main function with methane header, worth the gains achieved in the booster's control system during landing? This is a question that the management of SpaceX is unlikely to be able, or, more importantly, willing to answer now.

IV. …

This section of the paper, which describes the solution to oxygen header tank problem of Starship booster, is currently closed to the public.

Conclusions

1. The completion by the end of 2025 of almost simultaneous important phases of programs for creation of two of the most promising rocket systems at the moment – Starship and New Glenn – as well as the accident during cryogenic tests of Starship booster V3 latest version on November 21, 2025, made it possible to analyze some of the fundamental design features of Starship and the reasons for its changes from version to version.
2. This analysis showed that seemingly inexplicable increase in the cross-section of pipeline supplying methane to the booster engines is caused by problems with steadiness of its supply during the rapid rotation of the booster around transverse axis during boostback maneuver.
3. In turn, increase in the speed of this maneuver, starting with the fifth Starship flight, is associated with desire to increase payload of the rocket system, thus reducing loss of characteristic velocity, and consequently, fuel consumption for the boostback maneuver.
4. It was also shown that all these problems could have been avoided by placing main oxygen tank in front of main methane tank.
5. The unprecedented transverse size of central methane pipeline led to the displacement of previously existing oxygen header tank in the center of main tank to its side wall, resulting in pipelines with at least 7 different lengths that will supply oxygen to the engines during the booster landing.
6. This, in turn, means that opportunities arise for the emergence of up to 7 new variants of Pogo-type auto-oscillations, which can lead to a booster disaster during landing.
7. Suppressing such a number of new Pogo variants using the flight experiment method employed by SpaceX, followed by recalculation and changing of engines operating modes, may be physically impossible.
8. …
9. …

Conclusions 8 – 9, concerning the solution to oxygen header tank problem of Starship booster, is currently closed to the public.

10. And an assessment of all the design solutions used in the development of the latest booster version approve that full-fledged control over Starship program has essentially been lost.

Links

1. Yu. I. Lobanovsky – Why did New Glenn's booster only land on its second flight? *Synerjetics Group*, 30.11.2025, 9 p. // http://www.synerjetics.ru/article/NG_landing_eng.htm
2. Yu. I. Lobanovsky – Cause of Starship crash on first flight. *Synerjetics Group*, 05.10.2023, 19 p. // http://www.synerjetics.ru/article/starship_crash_eng.htm
3. Yu. I. Lobanovsky – Causes of Starship both stages crashes on second flight. *Synerjetics Group*, 04.12. 2023, 10 p. // http://www.synerjetics.ru/article/second_flight_eng.htm
4. Yu. I. Lobanovsky – Paradox of Starship two flights and its resolution. *Synerjetics Group*, 30.03.2024, 16 p. // http://www.synerjetics.ru/article/paradox_eng.htm
5. Yu. I. Lobanovsky – Second crisis of Starship program. *Synerjetics Group*, 30.03.2025, 11 p. // https://www.synerjetics.ru/article/second_crisis_eng.htm
6. Yu. I. Lobanovsky – Why did Starship second stage not explode in the ninth flight, but instead began to spin uncontrollably? *Synerjetics Group*, 15.05.2025, 10 p. // http://www.synerjetics.ru/article/ninth_flight_eng.htm

7. RGV Aerial Photography. *Reddit*, November 23, 2025 // https://www.reddit.com/r/SpaceXLounge/comments/1p4y1p7/detailed_views_from_inside_the_booster_18_aft/
8. Feeding the Beast: Super Heavy's Propellant Distribution System. *Ringwatchers*, 17 December 2023 // https://ringwatchers.com/article/booster-prop-distribution
9. RGV Aerial Photography – @RGVaerialphotos. *X-Post*, November 29, 2025 // https://x.com/RGVaerialphotos/status/1994828711816818845?s=19
10. Yu. I. Lobanovsky – Mechanism of Starship first stage explosion during its return maneuver. *Synerjetics Group*, 12.01.2024, 10 p. // https://www.synerjetics.ru/article/boostback_eng.htm
11. Lernaean Hydra.*Wikipedia* // https://en.wikipedia.org/wiki/Lernaean_Hydra

Moscow,
14.12.2025

Yu. I. Lobanovsky