The 13/33 engine exchange as a mirror of SpaceX's design approach

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Abstract

This paper demonstrates that the only reasonable explanation for attempting a 33-engine boostback burn during the twelfth Starship flight – instead of the standard 13-engine configuration – was an effort to prevent the excitation of Pogo auto-oscillations in new V3 booster version during this specific flight phase. Increasing the number of engines participating in the maneuver by 2.5 times would allow SpaceX to throttle their thrust down from nominal levels to the near-minimum allowable limit of approximately 40 %. This operational shift would increase the frequency of hydroacoustic oscillations within the booster's propellant system by a factor of about 1.6, which SpaceX anticipated would safely move the vehicle out of the high-risk Pogo zone. Utilizing such agile, "blind" design methodology stems from the fact that Pogo theory remains elusive to the company, and constructing dedicated ground-based test stands followed by prolonged research into Pogo suppression doesn't align with SpaceX's rapid timelines.

However, the inherently lower operational stability of rocket engines at the bleeding edge of their allowable envelopes led to multiple engine failures and the explosion of at least one unit. These anomalies occurred upon ignition during the highly dynamic and complex pitch-around maneuver at the start of the boostback. Ultimately, this resulted in the failure of the maneuver itself and the apparent destruction of the booster during its soft splashdown attempt.

Key words: *Starship, Pogo, crash, agile methodology*

I. Description of paradoxical booster boostback attempt in Starship flight 12

During the twelfth flight of Starship on May 22, 2026 – the first flight of new V3 version – the boostback procedure (the braking of the first stage – booster after stage separation and the reversal of its flight trajectory in the opposite direction to return to the launch site) began to be executed completely differently than in previous flights of V1 and V2 versions. Firstly, during the hot staging, not only were the 3 center engines kept running, as before, but also 2 out of the 10 inner ring engines, symmetrically located relative to the booster's central axis, weren't shut down. Furthermore, there was also an attempt to utilize 20 outer ring engines during this flight mode, which had previously been ignited only once on the ground [1]. Prior to this flight, only 10 inner ring engines were ignited during the boostback burn after stage separation.

According to the engine operation visualization data, after the remaining inner ring engines began to ignite, they appeared to shut down again for a fraction of a second, but then all of them, except for engine E12, started operating more or less steadily. Following this, the outer ring engines (which was previously physically impossible) began to ignite in two symmetrical groups of 10 (staggered in an every-other-engine pattern), also in a somewhat unstable mode. At that moment, engine E6, which had been running continuously since liftoff, exploded, and several surrounding engines ceased operating almost immediately. A fraction of a second later, only 10 engines remained running, then 5 outer ring engines were shut down, leaving only 5 inner ring engines operating, which were capable of thrust vectoring. These were mostly the engines furthest from the explosion site, but soon they were also shut down. Nevertheless, they managed to stabilize the booster, which had begun to rotate rapidly and erratically due to thrust asymmetry, demonstrating the outstanding performance of its control system under severe accident conditions.

Subsequently, the booster continued on its original trajectory and decelerated aerodynamically, with its deceleration parameters differing little from those of previous launches [2], except, naturally, for the opposite flight direction. This indicates that it remained fully controllable throughout this section of the trajectory. However, following an attempt to ignite the engines for the landing burn at an altitude of approximately one kilometer above the ocean, an explosion occurred 2 to 3 seconds later, which apparently completely destroyed booster B19. This marked the second anomalous destruction of the new version of the booster. The first had occurred 7 months earlier, when booster B18 was completely destroyed during ground testing [3].

Previously, during stage separation, 3 center engines ran continuously, and 10 additional inner ring engines were ignited during the boostback burn. In the 7 most recent flights, from the fifth to the eleventh, these 13 engines operated at nominal thrust, providing an acceleration of about 43 m/s² [4], which resulted in a sufficiently efficient maneuver and, at the same time, didn't place an excessive load on the booster's structure. Therefore, the attempt in the twelfth flight to ignite all 33 of the booster's engines left perhaps all competent external observers in a state close to amazement – why was this done? As a result, several explanations soon emerged, which, upon any close examination, don't withstand the slightest criticism: "testing the full thrust of the new Raptor-3 engines" (why?), "radically reducing the maneuver time" (but what would happen to the booster's structure in that case?), "eliminating the complex selective ignition system" (meaning the removal of shut-off valves on each individual engine – an action that would be far beyond the fundamental principles of design).

It is hardly worthwhile to further analyze all these assumptions due to their almost complete impracticality or meaninglessness. After all, a significant increase in the booster's propulsion system's thrust during the boostback burn leads to structural loads that are completely unacceptable from an engineering standpoint, especially considering the asymmetrically located landing oxygen tank in V3 version. In the author's view, these were attempts to explain the unexplainable under the influence of a shock caused by witnessing a completely paradoxical picture. However, even these commentators rather quickly came to the opinion that during the boostback burn in the twelfth flight, an attempt was made to change 13 engines operating at nominal thrust for 33 engines operating at maximum possible throttling – that is, at a thrust of about 40 % of nominal [5], which results in practically identical thrust for the entire propulsion system. And why this was done, despite the decrease in the efficiency and stability of the propulsion system's operation, was explained as mentioned above. However, if one considers the entire testing process of Starship starting from the first flight on April 20, 2023, while also taking into account the information that SpaceX has withheld over these 37 months, as well as the mentality of its head and chief designer, E. Musk, the solution to this paradox becomes quite obvious.

II. Explanation of the observed phenomenon

Thus, let us briefly describe the part of the information available to the outside world about all twelve Starship test flights through the prism of an idea that ties together all the nuances and paradoxes that occurred throughout this period of time.

1. During the first test flight, Starship, as a two-stage stack, experienced severe, highly characteristic, and seemingly unprecedented longitudinal oscillations (in the form of so-called "superspikes") with a period of about 12 seconds. As shown in study [6], these arose due to attempts by the rocket's advanced control system to suppress a Pogo-type auto-oscillation process that had emerged at the time by temporarily reducing thrust. This process occurs when the frequencies of the airframe's longitudinal elastic vibrations and the hydroacoustic oscillations within the rocket's propellant system are closely matched or are multiples of each other. Approximately 145 seconds into the flight, the rocket lost control and was soon detonated.
2. The hot-staging interstage adapter, urgently developed and integrated into Starship's design between the first and second flights [7], altered the own frequency of the structural longitudinal elastic oscillations of the stage stack, causing Pogo process to disappear in this flight mode. Simultaneously, during these 7 months, the stage separation scheme was completely modified through the transition to hot staging. Thus, essentially, it was the first fundamentally new Starship version that embarked on the second flight, even though it didn't receive a corresponding designation [8].
3. At the same time, a ban was placed on the word "Pogo" within SpaceX [9, 10].
4. In late spring – early summer 2023, the author of this work constructed an integral theory of Pogo, from which (with large pressure drops on the pump, typical for the fuel system of Starship's Raptor engines) a simple relationship followed between the frequency of hydroacoustic oscillations in the pipelines supplying fuel to the engine and its operating mode (with a fixed geometry of the fuel system) [6].
5. During the first boostback attempt in the second flight in November 2023, the booster exploded due to Pogo while performing its own separate flight [11]. The second stage also exploded during the dynamically relatively calm final phase of its acceleration [12].
6. At the turn of 2023/2024, the paper on Pogo theory mentioned in paragraph 4 – which described the indicated relationship between the frequency of hydroacoustic oscillations and the engine's operating mode, but didn't show the corresponding equations or describe the methods for their solution – became accessible to SpaceX [9].
7. One and a half to two months after that, in the third flight during the boostback burn, based on the hydroacoustic and elastic oscillation frequency data from the second flight and in accordance with the aforementioned relationship, the engine thrust was reduced by 15 – 20 %, and the booster didn't explode [9]. However, right at the very end, auto-oscillations began to excite, and as a result, the shutdown of the booster's engines after the boostback burn didn't occur strictly simultaneously. Because of this, the booster's return trajectory, as is well known, deviated quite significantly from the calculated one [13].
8. In the fourth flight during the boostback burn, the thrust was reduced by another 3 % (to approximately ~ 70 % of nominal), and this phase was completed fully successfully [4].
9. In the fifth flight, SpaceX took a risk: the engines quickly passed through the dangerous regime, and the thrust during the boostback burn was quite successfully brought up to nominal. After that, up until the most recent twelfth flight, the boostback burn was always performed in the same manner: with the ignition of 13 engines operating at nominal thrust (or, when isolated engine failures occurred, with 12 engines running for a slightly longer duration) [4].
10. Something similar was happening with the second stage. Following its explosion during the second flight (which, as it turned out later, was due to auto-oscillations involving the excitation of hydroacoustics in the vacuum engines' methane feed line), the standard method for combating Pogo became shutting them down 20 to 30 seconds prior to the end of the ascent phase on all V1 version second stages, that is, up to and including the sixth flight [14].
11. In order to avoid this on V2 version of the second stage, one could have taken the traditional route and developed dampers to suppress hydroacoustic oscillations, or simply calculated a safe pipeline length using the new theory. Instead, SpaceX is known to have created a completely new feed system for the vacuum engines featuring

three separate long pipelines instead of the original single manifold with six relatively short branches leading from it to each of the six engines, anticipating that such a pipe configuration would ensure the absence of Pogo [15].

12. At the same time, it can be noted that at the turn of 2023/2024, the author was unaware of the second stage methane feed pipeline design with its branching prior to the engines. Thus, he was essentially evaluating the possibility of Pogo occurring via this line for separate long pipelines exactly like those that eventually appeared in V2 version, and concluded that they were safe [11]. And it was precisely this configuration that appeared a year later on the second stage of Starship [15].

13. With this pipeline design option for the methane feed, Pogo-type auto-oscillations did indeed disappear. However, during the first flight of V2 version (the seventh flight overall), SpaceX suddenly discovered that the long, thin, and unsupported pipelines passing through the oxygen tank experienced transverse resonant vibrations. Consequently, one of them failed at a relatively late stage of the second stage's ascent, when most of the oxygen had been consumed and ceased to dampen these transverse oscillations [15].

14. After these pipelines were reinforced, Pogo-type auto-oscillations suddenly arose at a slightly later stage of the ascent, this time within the oxygen line (as calculated in that early paper) [11]. As a result, in subsequent flights, the vacuum engines still had to be shut down during the final phase of the ascent [15].

15. In flights seven through eleven, the same version of the booster was used as before, so there were no issues with auto-oscillations on the booster during these flights.

16. The need to increase the payload capacity delivered by Starship required a transition to the its new V3 version, in which both the first and second stages were modified, and Raptor-2 rocket engines were replaced with more advanced Raptor-3 engines. In the process, essentially all the empirical data regarding operating modes safe from Pogo-type auto-oscillations – obtained at the cost of six explosions and two critical losses of orientation over 11 flights of the previous versions of Starship – lost their value. The recalculation of the engine operating mode using a simple formula after another excitation of Pogo, which had been used by SpaceX, naturally became impossible again; it was necessary to solve the equations describing the process, but SpaceX didn’t and doesn’t have them.

17. The company was left with no choice but to restart the flight cycle with empirical searches for modes dangerous in terms of auto-oscillations. From the accumulated experience, it could be understood that a sharp reduction in engine thrust during the boostback burn – the most challenging mode for them – could ensure the absence of Pogo. And then, the "13/33 exchange" was made: it was decided to increase the number of active engines during the boostback burn from 13 to 33, i.e., by 2.5 times, while their thrust was also to be reduced by 2.5 times, down to the maximum possible throttling level (the minimum mode of stable operation) – to 40% of nominal [5]. In this case, the frequency of hydroacoustic oscillations would increased by nearly 1.6 times and would clearly leave Pogo zone, the boundaries of which had shifted due to changes in the booster's mass, the length of its pipelines, and the combustion chamber pressure of its engines.

18. However, this engine operating mode near the lower allowable limit of operation is in itself less stable than at high thrust close to nominal. Furthermore, the boostback burn is the most difficult mode for engine operation, since at this time the booster, experiencing significant load factors (up to ~ 4.5), performs intense attitude change maneuvers, flipping by ~ 180°.

And, as the flight experiment demonstrated, the engine restart failed [1]. Fig. 1 shows 12 sequential images of the propulsion system's status at that moment from source [16], which utilized images from the engines status screen on video [1] slowed down by a factor of 4. Here, the white circles represent operating engines, dark gray indicates shut-down engines, light blue represents igniting engines, purple indicates shutting-down engines, light brown represents engines that lost thrust and control prior to the explosion of engine E6, and dark brown – after its explosion. The light chocolate color of engine E6 and the circle of the same color around it in the far-right image of the middle row in Fig. 1 indicate its explosion and the propagation zone of its explosive shockwave at that moment. Although these images represent the real changes in the propulsion system's status at the moment of the attempted boostback maneuver only to a fairly low degree, even they show how chaotically the engines reacted to the highly explicit startup sequence described at the beginning of the article. And yet, it seemed as though it was almost successfully executed – with the exception of three engines that joined the outer ring engine E30, which had been completely shut down long before, the remaining 29 engines were either already operating in the minimum mode or were igniting (see the right-center image in the middle row). However, at that moment, the inner ring engine E6, which had been running continuously since liftoff, exploded, and the shockwave from it extinguished all engines except for ten (see the left-center image in the bottom row). Immediately following this, all five remaining fixed-thrust outer ring engines were shut down so that they don't interfere with the stabilization of the booster using the five vectoring engines of the inner ring.

Although the booster didn’t destroy itself afterward and even miraculously maintained its attitude and control, its flight in the opposite direction from the intended path ended in an explosion and destruction during the ocean landing attempt.

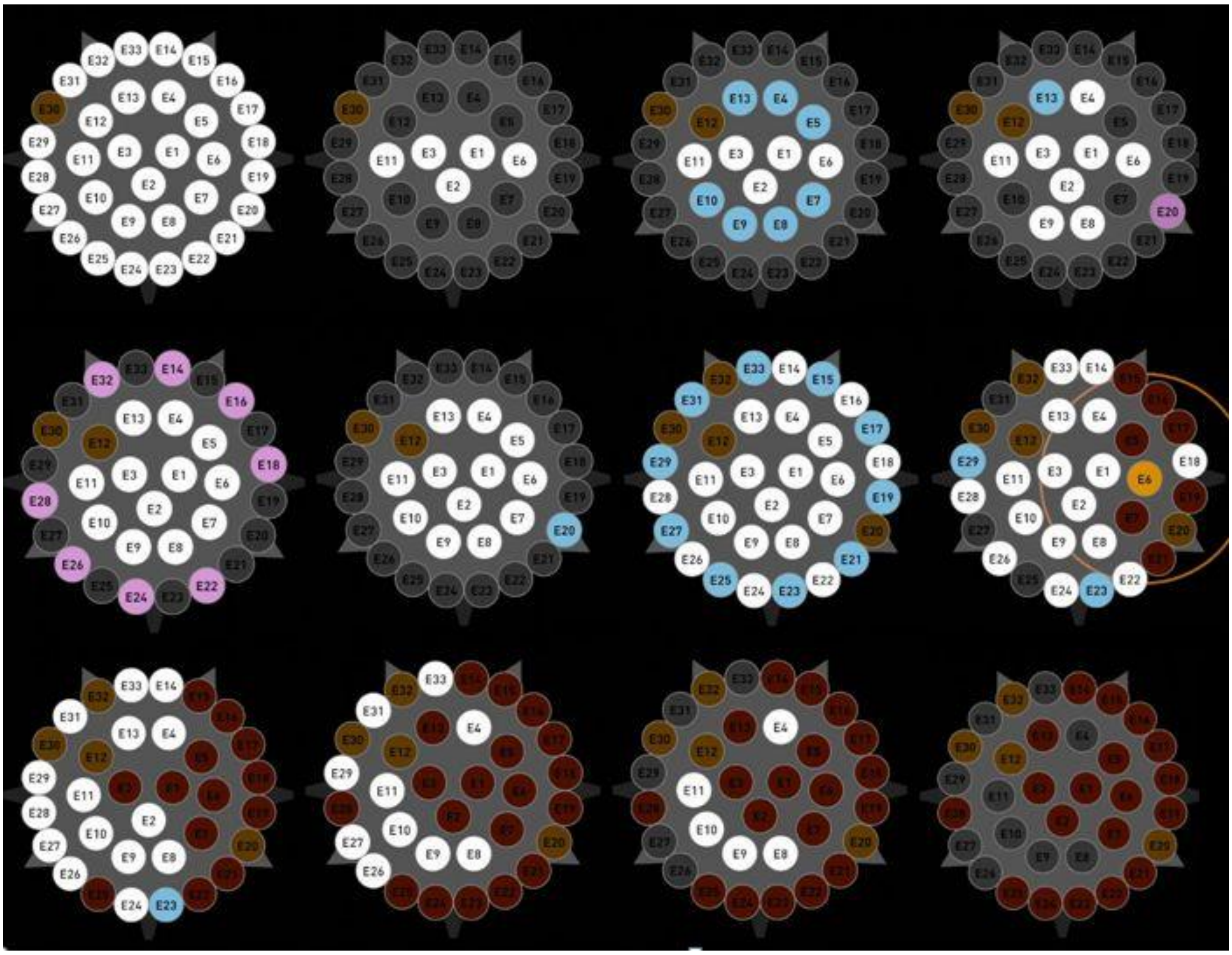

Fig. 1 – 12 sequential images of the booster propulsion system's status during the attempted boostback maneuver

III. The 13/33 exchange and SpaceX's design method in the Starship program

In the Starship program, as in all others, SpaceX utilizes the agile design method. Its core principle is rapid prototyping, in which a currently feasible and not overly thoroughly developed prototype of the final product is tested, data is collected (in rocketry, usually after its loss), and the product is upgraded based on the test results. It is then tested and upgraded again, and this cycle continues until a final product is obtained that satisfies the requirements of the developer and/or the customer, or until the project is terminated.

This inherently implies the use of a fairly large number of system's versions under development and a high volume of tests. However, when the system under development is complex enough for processes to occur within it that aren't fully controlled by its creators, the number of system versions and tests can grow indefinitely. Although testing is conducted precisely to identify and eliminate factors and circumstances that were overlooked during preliminary design, the emergence of uncontrolled or poorly understood processes can completely break down the entire agile design procedure. It ceases to converge toward what could be recognized as a final design result.

It is quite possible that the multiple manifestations of Pogo-type auto-oscillations in the Starship project may turn out to be such processes. When SpaceX unexpectedly encountered Pogo after the first flight, this challenge was met with a swift response in the best traditions of agile design. In doing so, apparently assuming that it was an isolated episode, it was decided not to disclose this information at all. However, these challenges began to multiply, demanding qualitatively different responses. Since a full theory of Pogo was unknown to SpaceX at that time, combating it required the creation of complex ground test rigs and fairly lengthy research, which didn't fit into SpaceX's paradigm – that is, into E. Musk's style. It is unknown how all this would have ended – perhaps soon even with the termination of the Starship project – had SpaceX not suddenly gained access at that same time to a formula for recalculating hydroacoustic oscillation frequencies according to the rocket engine's operating mode, the use of which aligned well with the principles of agile design. By the fourth or fifth flights, all manifestations of Pogo on the V1 version had been suppressed.

However, in the subsequent V2 version of Starship, which featured an enlarged second stage, the company would have had to go down the same path again – endure at least one explosion and then use the gathered data to recalculate the engine operating mode. Seeking to avoid such a scenario, SpaceX decided to utilize already published data for a design known to be stable against longitudinal auto-oscillations, which featured separate long methane feed lines to the engines. However, the company failed to foresee other problems and consequently spent the first 3 flights of V2 version once again working to suppress Pogo.

A similar situation arose again during the transition to the V3 version – unable to calculate the frequency of hydroacoustic oscillations to guarantee the suppression of Pogo-process, which was bound to occur on the new booster at a different frequency, it was apparently decided to shift this frequency as drastically as fundamentally possible. To achieve this, the outer ring engines were equipped with in-flight ignition capabilities, and the "13/33 exchange" was implemented: instead of operating at nominal thrust, the engines were supposed to run at a near-minimum setting during the boostback burn. However, just as in the first flight of V2 version, not all factors were taken into account, and SpaceX suffered a new anomaly and a new explosion in the twelfth flight. We are witnessing how, for the third time now, everything is back to square one. And it seems that with such an approach to developing a highly complex system like Starship, it will always be this way – with any modification, a new cycle of tests accompanied by anomalies and explosions will be required every single time.

Conclusions

1. The attempt to ignite all 33 engines for the boostback burn during Starship twelfth flight, instead of the usual 13, was driven by the desire to avoid the excitation of Pogo-type auto-oscillations in this flight mode on the new V3 booster version.
2. Increasing the number of engines participating in the process by 2.5 times made it possible to reduce their thrust from nominal to the minimum allowable level – down to 40 % of nominal.
3. This would have increased the frequency of hydroacoustic oscillations by approximately 1.6 times and, as SpaceX expected, would have move out this frequency from Pogo zone.
4. .However, the lower operating stability of the rocket engines at the boundary of allowable operating modes led to their multiple failures and even the explosion of one of the engines upon ignition during the highly dynamically complex phase of initiating the boostback – the turnaround of the booster for flight in the opposite direction.
5. The failures of the majority of the engines led to the abortion of the maneuver and, apparently, to the explosion of the booster during its soft splashdown attempt.
6. Such a "blind" design method was driven by the fact that the Pogo theory is inaccessible to the company, while building ground experimental test stands first and then conducting lengthy research to suppress Pogo isn't part of SpaceX's plans.
7. Moreover, in order not to reveal its weaknesses, the company completely withheld information regarding the very existence of these dangerous processes.

Links

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