Analysis of Landing Failures of Starship V3 booster

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Abstract

The excitation of Pogo-type auto-oscillations was a problem not announced by SpaceX, yet one that loomed over the entire development program of the reusable Starship rocket system. As a result of 11 flights conducted between April 2023 and October 2025, the company succeeded in developing one version of the first stage and two versions of the second stage which became capable of flying without exhibiting of Pogo.

However, last year's structural analysis of the landing propellant system of Starship V3 booster, combined with the results of its two flight tests in May and July 2026, demonstrated that Pogo oscillations have returned again during the booster landing phase, and apparently in increased numbers. Specifically, following the second failed flight of the new version booster, three 3 pairs of engines from inner ring, which should have the same frequency zones of excitation of auto-oscillations, were unable to start or reach operating mode. In the existing configuration of the landing propellant system, this constitutes an obvious indicator of Pogo interference. Consequently, the resulting insufficient and asymmetric thrust led to the destruction of the booster during both landing attempts.

Keywords: *Starship V3, Pogo oscillations, failure, V3 version*

I. Brief Overview of Flight Test Results for Two Preceding System Versions

Currently, within the framework of an agile methodology, the flight testing of Starship V3 system is underway. On May 22 and July 24, 2026 – more than three years after the initial suborbital flight – the first and second launches of this vehicle version were executed, marking the twelfth and thirteenth launches since the inception of the suborbital flight program.

Flight testing of the first version of the vehicle spanned 18 months, encompassing a total of six launches. The primary objective of this testing phase proved to be the detection and mitigation of multiple instances of Pogo oscillations, an issue about which SpaceX never disclosed a single word [1]. A Pogo phenomenon occurs when the frequencies of hydroacoustic oscillations within the pipelines delivering propellant to the rocket engines resonate with, or become harmonics of, the natural longitudinal structural vibration frequencies of the vehicle's airframe. Utilizing an approximate formula relating the frequency of hydroacoustic oscillations to the engine operating mode – derived by the author of this paper two months after the initial Starship launch [2] – SpaceX successfully mitigated all instances of Pogo excitation on the first version of the system by the fourth and fifth test flights. However, this was achieved at the cost of implementing certain operational restrictions on the engines, which reduced payload delivery efficiency. Ultimately, these measures enabled the first successful recovery and catch of the Super Heavy booster (the system's first stage) by the launch-landing complex manipulators, while the Ship (the second stage) demonstrated the capability to return to the ocean from a suborbital trajectory in a relatively intact state. Nevertheless, despite this highly significant progress during the initial testing phase, the payload capacity of the first Starship version proved to be near-zero, necessitating the development of a new version with a substantially higher liftoff mass.

However, this required the development of a new version of the rocket engines with significantly higher thrust, as it was virtually impossible to install additional engines on the 9-meter-diameter first stage beyond the 33 existing Raptor 2 units. At the same time, uprating and downweighting the Raptor 2 engine – which already possessed record-breaking performance characteristics – proved to be a fairly prolonged process. Consequently, SpaceX decided to develop the second version (V2) of Starship system as an interim step between the first iteration (V1) and the target V3 version, which, according to plans, could already be operated, albeit in a limited capacity. The V3 version was intended to enable the deployment of the new, substantially heavier Starlink V3 satellites, as well as to provide initial lunar access under the Artemis program.

Consequently, flight testing of the second version of Starship rocket system commenced in January 2025 and spanned approximately nine months. The engines and the booster remained unchanged in this iteration; the only modifications involved expanding the propellant tanks of the second stage by slightly increasing its length and reducing the payload bay volume, alongside redesigning the forward flaperons' placement and the methane feed system for the stage's three outer vacuum-optimized engines. These adjustments were implemented to eliminate Pogo during the terminal phase of the second stage's ascent, an issue that had ultimately been addressed in the first version simply through early engine shutdown. In total, five launches were executed, as one of the six constructed Ships exploded on the ground during static fire testing. The boosters, having been refined during the previous test series, operated almost flawlessly and were reused twice; however, the first three flights of the second-version ship (the seventh through ninth launches overall) concluded catastrophically [1, 3].

In the seventh flight, the failure was caused by ordinary transverse harmonics vibrations within the new, elongated, thin, and unbraced methane feed lines leading to the outer engines. After the developers resolved this issue, the eighth flight unexpectedly experienced "good old" longitudinal auto-oscillations during a slightly later stage of the ascent trajectory. This time, however, the oscillations occurred in the oxygen feed lines, a possibility that the author of this paper had warned about as early as a December 2023 study [4]. Consequently, SpaceX had to revert to the practice of shutting down the outer engines before reaching the target velocity. Nevertheless, during the ninth flight, the recalculation of the engine performance characteristics was apparently inaccurate; the manifestation of Pogo oscillations during the shutdown of the center engines induced an unrecoverable roll of the second stage, leading to an uncontrolled atmospheric re-entry and subsequent destruction [3]. During the final two launches, the operating modes of the second-stage engines were adjusted more precisely, and both flights concluded successfully. However, it can hardly be considered a coincidence that the payload for the seventh flight – 10 mass simulators of Starlink satellites (weighing ~ 20 metric tons) – was subsequently reduced to ~ 16 metric tons (8 mass simulators). Fine-tuning the second stage seemingly cost 20 % of the already highly limited payload capacity of Starship V2 system. Thus, the approximately 18-month period from November 2024 to May 2026 (spanning from the final flight of the first version to the inaugural flight of the third) wasn't highly productive in terms of acquiring flight data for system refinement, except that the final two flights of the second version demonstrated positive dynamics in the development of the second stage's thermal protection system. This stagnation occurred amid persistent schedule slippages and breached contracts under the Artemis program. Such was the price of an inability or reluctance to fully utilize the theory of Pogo auto-oscillations, rather than relying solely on its single corollary available to SpaceX – using experimental data from a catastrophically failed previous flight to correct engine operating modes in the subsequent one.

II. Projection of Probable Landing Failures for Starship V3 booster

Initially, the inaugural test flight of Starship V3 system was projected to occur three to four months after the final flight of V2 version, placing it in early 2026. This version was equipped with lighter Raptor 3 engines delivering approximately 10 % more thrust than their predecessors; the propellant capacity of the first stage and its liftoff mass increased by a similar margin. The second stage also received new engines, and its propellant mass expanded by approximately 6.5 % while maintaining its original length. Unlike the second stage, the first stage's propellant system underwent radical structural modifications, which are described in detail in reference [5]. Of particular significance, as was immediately apparent, was the replacement of the coaxial oxygen landing header tank with a new landing tank positioned asymmetrically to the side of the new central methane feed downcomer. A booster featuring this design immediately suffered a failure as early as the ground pneumatic testing phase. This accident provided an opportunity to look inside its ruptured hull and discern the general configuration of the feed lines delivering liquid oxygen from the landing header tank to the engines, as shown in Fig. 1.

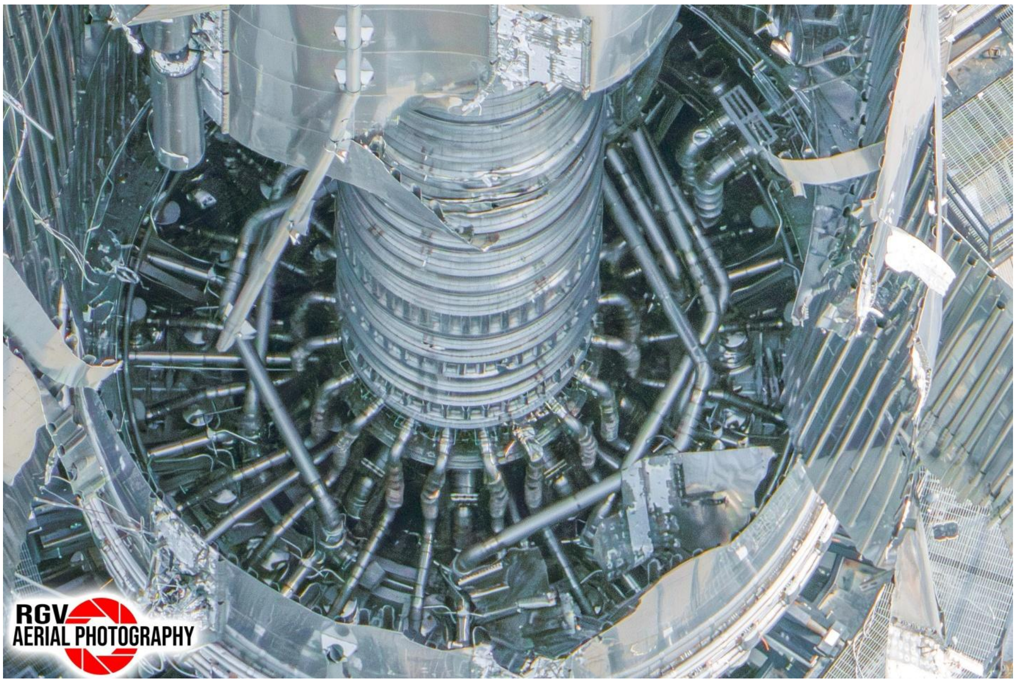

Fig. 1 – Visible section of the feed lines running from the side oxygen landing header tank to the engines of B18 booster [6]

From the very first glance, it became evident that the third phase of test flights wouldn’t proceed smoothly. As early as a December 2025 paper [5], the author noted:

- "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.
- 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.

- 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".

This eight-month-old prediction is perfectly validated by the outcomes of the two recent test flights involving Starship V3 booster – the twelfth and thirteenth launches conducted in May and July 2026. In both instances, B19 and B20 boosters failed to execute a soft ocean splashdown [7, 8]. For more than a month and a half following the twelfth flight, explanations of the incident were confined to abstract statements regarding "heat effects on propulsion system components during the ascent and erroneous engine alarm system settings" [9]. It was also reported that the necessary modifications had been implemented. Nevertheless, in the subsequent thirteenth flight, the booster landing concluded with essentially the same outcome, even though a greater number of engines ignited on this occasion.

III. Analysis of the First Two Failed Landing Attempts of V3 booster

During the first booster landing attempt, the vehicle's velocity and altitude were displayed on screen at the moment of engine ignition, whereas during the second attempt, the altitude along with the number of igniting and operating engines were shown. The final altitude at which the booster's velocity could be observed during the thirteenth flight was approximately 7.2 km. Because only 5 of the 33 engines reached operational mode during the boostback burn of the twelfth flight [10] – the trajectory reversal maneuver intended to return the booster to the launch site, where all 33 engines were supposed to ignite simultaneously for the first time instead of the previous 13 – this maneuver failed. Following stage separation, the booster proceeded along an off-nominal trajectory, with its splashdown point located more than 300 km away from the target point [11], and its downrange velocity significantly exceeding the planned values. At an altitude of 7.2 km, this velocity was approximately 820 m/s, whereas during the second landing attempt, when the flight trajectory was close to nominal, the velocity was about 575 m/s. At the moment when the first glints of the engine exhaust plume became visible on the video feed, the velocity during the first landing attempt was ~ 430 m/s (see Fig. 2 at timestamp 6:11). Extrapolation of the available data for the second landing attempt yields a value of approximately 325 m/s, which virtually coincides with the velocity at which the landing engines of B11 booster began operating during the first successful soft splashdown more than two years ago [12].

Fig. 2 – Trajectory and other telemetry data during the boostback burn and landing burn attempts of B19 booster [13]

Fig. 2 illustrates which 5 engines operated during the boostback burn attempt of B19 booster (at timestamp 2:40), as well as its velocity and altitude values at the inception of the landing burn attempt (at the 6:10 – 6:11 mark) and just prior to water impact and subsequent destruction (at timestamp 6:15). As follows from further consideration, the engines that tried to turn on (if there were more than one) not only failed to increase the deceleration force acting on the booster but actually significantly reduced its aerodynamic drag. Most likely, an ignition attempt occurred for only one or a very small number of the five engines seen operating in the upper section of Fig. 2. All of these were inner ring engines, which lack thrust vector control capabilities.

Based on the video data [13], the booster's accelerations and load factors n were determined for the final 16 seconds of flight (5:59 – 6:15). Additionally, the flight Mach number M and the axial force coefficient C_x acting on the vehicle were calculated under the assumption that its mass prior to engine ignition was 210 metric tons (see Fig. 3). Up to the timestamp of 6:11 – corresponding to point 13 in Fig. 3 – the coefficient C_x was determined solely by aerodynamic forces, and it varied from approximately $C_x \approx 2.0$ to $C_x \approx 1.25$ within the Mach number range of $M \approx 2.25 – 1.35$. This agrees well with the drag coefficient of a high-aspect-ratio cylinder with a flat forward face at identical Mach numbers $C_D \approx 1.7 – 1.3$, as shown below in Fig. 4 (here $C_D \equiv C_x$). It should be noted that the maximum drag coefficient of a cylinder with a rounded end doesn't exceed a value of $C_D \approx 0.6$. But the bottom end of the booster features numerous engine nozzles – components with substantial cavities – and therefore, its drag coefficient, prior to the onset of gas exhaust from the engines, should be higher than that of a flat-ended cylinder. The booster drag coefficient obtained in our estimations is directly proportional to its current mass. The value selected for the calculations (dry mass combined with propellant residuals) – 210 metric tons – appears highly reasonable; however, both the drag coefficient and the landing mass of B19 booster may certainly deviate slightly from these figures. Nevertheless, this will in no way affect the primary conclusions that can be drawn from the presented information.

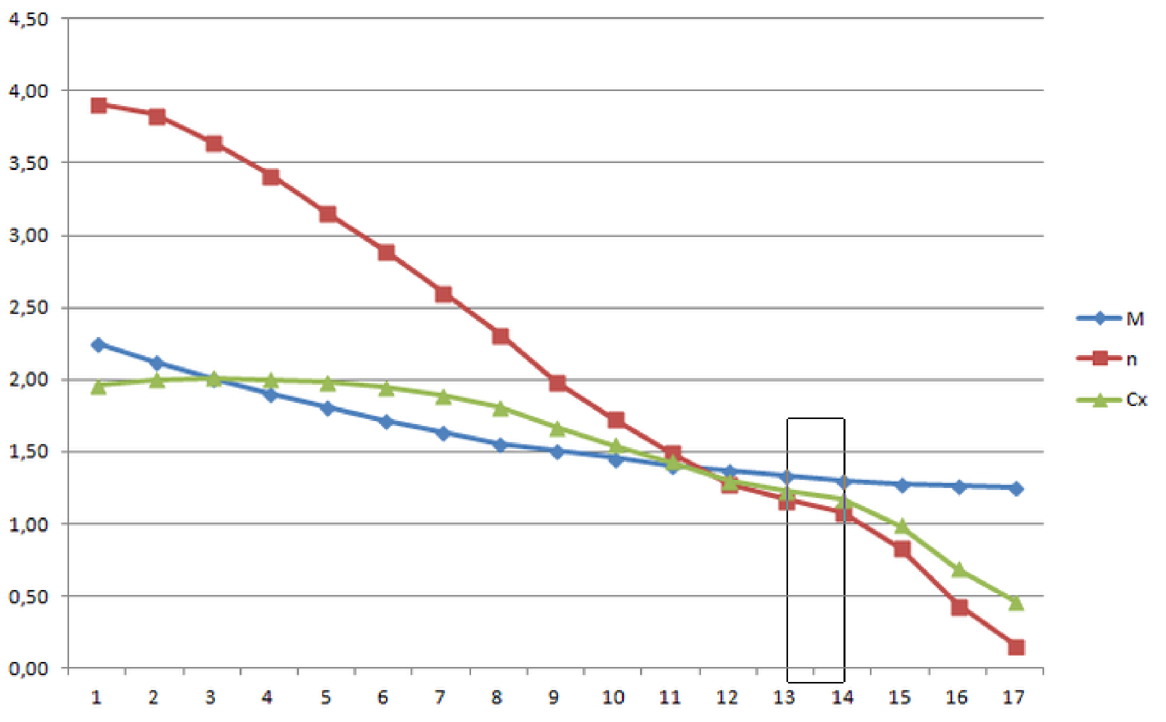

Fig. 3 – Estimations of Mach number M, longitudinal load factor n, and axial force coefficient C_x for B19 booster during the terminal trajectory phase prior to water impact

What is significantly more interesting is that following the onset of engine/engines operation (a moment highlighted by the rectangle in the graphs of Fig. 3), the axial force coefficient not only failed to increase due to the addition of a thrust force directed opposite to the velocity vector, but, on the contrary, decreased sharply. But after all, the full thrust of a single Raptor 3 engine at that altitude should have been approximately 2.5 MN. For a booster's mass of ~ 210 metric tons, this would have added an increment of $\Delta n_e \approx 1.2$ to the aerodynamic drag-induced load factor, and even at a throttle thrust down to 40 % from nominal, the increment would be $\Delta n_e \approx 0.5$. Instead, the load factor dropped nearly to zero, and the axial force coefficient, which stood at $C_x \approx 1.25$ prior to engine ignition (but after the commencement of gas venting from the nozzles during startup sequences), plummeted to $C_x < 0.5$, approaching the values of a sharp-nosed cylinder (see Fig. 4). The total axial force became virtually equal to the booster's weight, and for the final 4 seconds of flight (6:11 – 6:15), from an altitude of about 1 km, the vehicle descended at an almost constant velocity despite some level of engine operation. More precisely, the booster fell in this manner because of this engine operation, since under "pure aerodynamics" it would have decelerated more intensively.

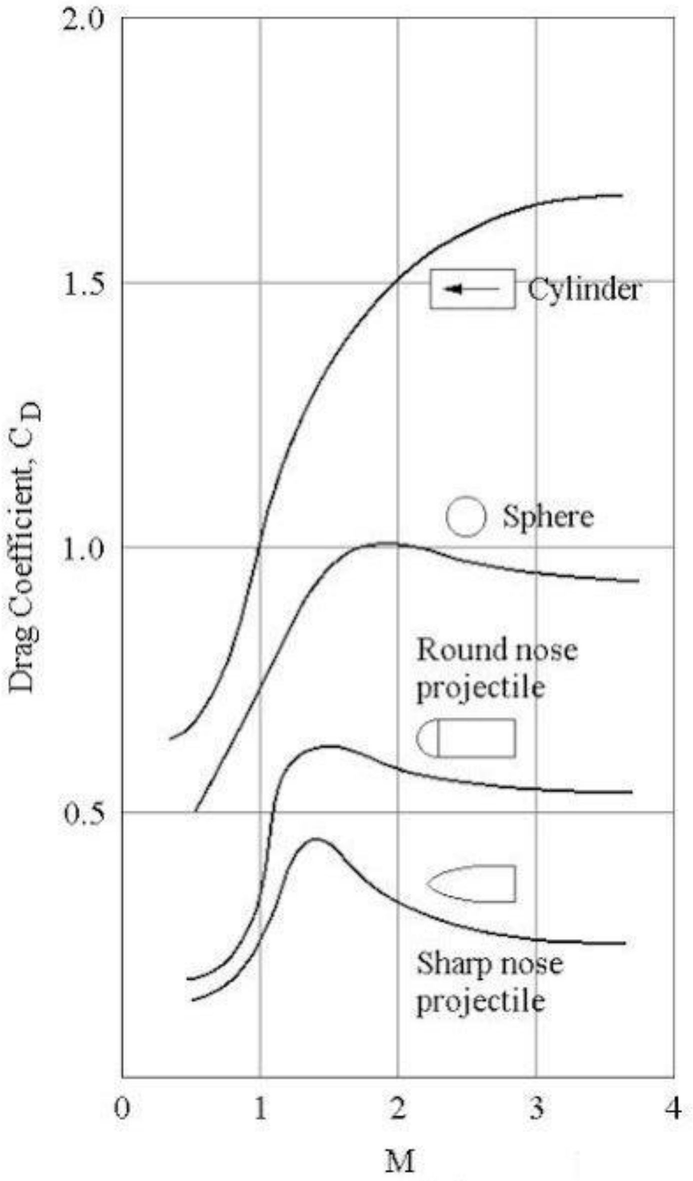

Fig. 4 – Drag coefficients of selected axisymmetric bodies [14]

The explanation for this paradox is fairly simple: it is well known from both physical experiments and numerical simulations that when a counterflowing gas jet is discharged from a nose cavity against an oncoming freestream at M ≈ 1.3, the aerodynamic drag of the body can decrease by up to 35 %. In the case under consideration, the situation is more complex due to the existence of at least 33 "cavities" and the asymmetry of thrust; this is likely why the reduction in the booster's aerodynamic drag proved to be even more pronounced. Ultimately, one point remains qualitatively clear: prior to touchdown, too few engines (apparently only one) ignited on B19 booster, and none of them reached even the minimum throttle capability. The jet that reduced the aerodynamic drag persisted for 4 to 5 seconds, whereas any discernible thrust failed to materialize entirely. Therefore, based on the data presented in Figures 2 – 4, it can be asserted that not a single engine on B19 booster started normally during the landing sequence.

Let us now examine the ocean splashdown attempt of B20 booster. Figure 5 illustrates the sequence in which the engines ignited and shut down during this phase. Ultimately, only 5 engines operated instead of the intended 13, preventing the booster from decelerating sufficiently and leading to its destruction upon water impact, albeit at a lower velocity. Unfortunately, no public trajectory data is available for this specific flight segment. However, extrapolation of the velocity from an altitude of 7.4 km down to 1.4 km – the engine ignition altitude – indicated that the velocity at that moment was between 325 and 330 m/s. This aligns precisely with the velocity data of all prior successful landings executed by the preceding booster version. Thus, it can be inferred that following almost completely successful boostback burn (which concluded with a minor shutdown timing discrepancy among the three center engines, causing a slight deviation from the target landing point), the trajectory parameters of B20 booster at the moment of landing burn ignition were virtually nominal, unlike those of B19 booster.

Однако, запуск 13 посадочных двигателей, судя по иконографике, продолжался 4 – 5 с, на However, judging by the telemetry graphics, the ignition of the 13 landing engines lasted for 4 – 5 seconds; while 10 out of the 13 engines responded to the control signals, only 5 ultimately ignited (see Fig. 5). Consequently, three pairs of deactivated, opposing inner ring engines were formed: E4 – E9, E5 – E10, and E6 – E11 (the engine numbering is provided in reference [15]). These engine triplets (E4 – E6 and E9 – E11) are located sequentially along the inner ring, with the first engine of each pair starting from the upper right of the inner ring, followed by clockwise counting, as shown in the lower inset of Fig. 5. The remaining two engines that failed to start – the central engine E2 and the upper left inner ring engine E13 – "flickered" for several video frames but eventually "went out." Overall, qualitatively, this pattern aligns with the author's prediction made immediately after the internal structures of the B18 booster became visible following its destruction during ground testing in November 2025: "...this [increasing the cross-section of the booster methane pipeline] 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" [5].

Fig. 5 – Activation and shutdown of B20 booster engines during its landing attempt [16]

And now, eight months later, we are witnessing this struggle firsthand, the results of which have already become available to the outside world. It is possible that during the first landing attempt of the new version of the booster, Pogo oscillation, if they were at all, occurred during the unsuccessful boostback burn, although that was more likely just the engines operating at the lower boundary of their stable functioning mode under dynamically challenging conditions [10]. Furthermore, the B19 booster arrived at the landing phase already in a semi-disassembled state, and, along a trajectory where the maximum dynamic pressure was approximately ~ 180 kPa, which is 1.8 times higher than the design value (about 100 kPa). At the moment the jet plume began to appear at an altitude of ~ 1.3 km, the dynamic pressure was close to 100 kPa, whereas during B20 landing, it was about 55 kPa. Notably, during the successful landing of New Glenn rocket booster in its second flight, the dynamic pressure at the moment of engine startup was ~ 30 kPa. Thus, it is entirely possible that in the first landing attempt of the new booster version, the freestream flow impinging on the nozzles simply "choked" those B19 booster engines that were still capable of functioning at that time. However, during the second landing attempt, already under design conditions, that very "sextet" about which a warning was issued eight months ago most likely began to play, and it played a melody called "Pogo". We shall see how many failed flights SpaceX will need to expel this "sextet" from the orchestra pit.

Conclusions

1. Multiple instances of Pogo-type auto-oscillations constituted a problem that, while unacknowledged by SpaceX, loomed over the entire development and evolution program of Starship reusable rocket system.
2. By utilizing a recount formula for the dependence of hydroacoustic oscillation frequency on rocket engine operating modes, and based on experimental data obtained during disasters incidents, SpaceX identified operating envelopes that didn't induce Pogo oscillations.
3. Thus, as a result of conducting 11 flights between April 2023 and October 2025, the company succeeded in developing one version of Starship system's first stage and two versions of the second stage capable of performing flights without manifestations of Pogo.
4. However, the very first incident involving the second version of the booster within the system's V3 iteration – the destruction of its first copy on the ground in November 2025 – led to the conclusion that the structural modifications introduced would highly likely result, at the very least, in multiple manifestations of Pogo during booster landing.
5. Two flights of Starship V3 system conducted to date have confirmed this assumption, at least judging by the results of its second flight.
6. While the failure of the booster's rocket engines to ignite during the first landing attempt can be explained by its approach to the Earth's surface along a highly unplanned trajectory, which subjected the booster's lower section and engine nozzles to excessively high dynamic pressure, in the second case, available data allow for a confident assumption that at least 3 pairs of inner ring engines, which pairwise must share identical frequency zones for auto-oscillation onset, failed to start or attain nominal thrust levels due to Pogo.
7. The resulting insufficient magnitude and asymmetry of thrust during the second booster landing attempt led to its destruction, just as occurred during the first attempt following the failure of its engines to ignite.

Links

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