Causes of Starship both stages crashes on second flight

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Summary

In this work, based on approaches described in the articles [1, 2], second test flight of Starship was analyzed and it was shown that loss of second stage at the very end of its active flight phase was caused by a self-oscillating process of Pogo-type, activated by hydroacoustic oscillations in oxygen supply lines to engines. It is also explained how the introduction of an intermediate interstage compartment called Forward Heat Shield Interstage (FHSI) for hot separation suppressed in Starship second flight that self-oscillating process at B9 stage, which at B7 stage in the first flight led to a rocket crash during its active flight phase. But, at the same time, this action ensured the emergence at B9 of another potentially more dangerous Pogo-type process, which simply didn't have time than to fully express itself.

Thus, method proposed in the article [1] for calculating hydroacoustic oscillations in propellant supply lines for liquid rocket engines with large pressure drops makes it possible in advance, before flight experiments, to quickly and easily detect and suppress manifestations of potentially dangerous combinations of technical characteristics of both the rockets themselves and their propulsion systems, which can cause destructive self-oscillations in flight, including catastrophic ones.

Keywords: *Pogo, self-oscillations, crash, Starship, frequency, excitation, hydroacoustic oscillations, own oscillations*

Symbol list

c – speed of sound
D – diameter
E – modulus of elasticity
f_e – own frequency of rocket hull
f_n – frequency of hydroacoustic oscillations
g – acceleration of gravity
L – length
L_{eq} – equivalent length of oscillatory circuit
m – mass
p – pressure
q – dynamic pressure
δ – wall thickness
κ – proportionality factor

I. Main events of Starship second test flight

As you know, 7 months after first Starship flight, which took place with multiple failures of engines and other systems, fires in the compartments, and ultimately ended with its explosion and destruction into separate fragments [1], its second flight took place on November 18, 2023 [3]. This time, throughout the entire acceleration active flight phase of the first stage and almost the entire active flight phase of the second stage, main events, as far as an external observer can judge, occurred exactly according to the plan, which was as follows (all times are indicated in minutes and seconds) [4]:

00:00:02 – Liftoff.
00:00:52 – Max q (moment of peak mechanical stress on the rocket).
00:02:39 – Booster MECO (all engines of the first stage except three central ones cut off).
00:02:41 – Hot-staging (Starship Raptor ignition and stage separation).
00:02:53 – Booster boostback burn startup – in reality, one of the engines didn’t turn on. Next in the plan there was a point:
00:03:47 – Booster boostback burn shutdown.

But, even while the engines were operating at the second working phase, they began to spontaneously turn off one after another, and 27 seconds before their scheduled shutdown, at 00:03:20, an explosion of the first stage – booster B9 occurred.

Meanwhile, S25 second stage continued to move along the acceleration trajectory without any visible problems. According to the plan, it was supposed to cutoff its engines at 00:08:33. Obviously, in accordance with the flight program, at 00:07:40, the engine thrust began to decrease slowly and in a controlled manner so that the acceleration of the second stage didn’t exceed 3.5 g. And 23 seconds after this, at 00:08:03 (30 seconds before the planned completion of acceleration), all engines of the second stage suddenly turned off, after another 2 seconds telemetry completely disappeared, and light translucent cloud began to expand in the sky where S25 was at that moment. It isn't known for certain what happened at that moment, and what happened next, however, an external observer recorded the flight of S25 in a relatively intact form through a telescope for at least another 64 seconds until 00:09:07 [5]. At the same time, it tumbled, streams of gases flowed out of it, but it stubbornly continued to fly. However, after some time, its fragments were recorded falling into the ocean near the island of Puerto Rico [6].

A comparison of the first and the second flights descriptions, as well as three static test engine starts at the launch position, leads any unbiased observer to three main questions:

4. Why was the behavior of the first stage, Super Heavy booster, so different during its acceleration phases in the first and the second flights?
5. Why after boostback burn startup did the avalanche-like emergency shutdown of the first stage engines occur?
6. Why, at the very end of the acceleration trajectory phase, after a long and uninterrupted operation, without any apparent reason did all the second stage engines suddenly shutdown at the same time?

This article is devoted to the answers to these questions. The first and third questions were answered quite clearly, that is, as definitely as possible in the absence of accurate data on Starship design characteristics. The answer to the second question turned out to be conjectural – two possible options were identified, the final choice of which could only be made by the developers of this rocket system, who know its characteristics, also received extensive telemetric information, and they could only do this using the theory described in paper [1]. Answers were also given to those important questions that an outside observer simply could not ask.

II. Why the behavior of Super Heavy, so strikingly was different during its acceleration phases in the first and the second flights?

The first flight of Starship was accompanied, as mentioned above, by a large number of failures at the flight trajectory of its first stage – Super Heavy (B7) and ended with a complete loss of control, detonation and destruction of entire B7+S24 assembly. In accordance with the ideas described in paper [1], all this happened and continued because of that intense self-oscillations of Pogo-type, which arose and continued in B7 almost throughout the entire acceleration time (except for the period of passage of q_{max} zone with reduced thrust) due to positive feedback between hydroacoustic disturbances in the methane supply lines to the engines and the own oscillations of rocket hull at a multiplicity of their frequencies. Despite the very large number of relatively minor changes in design of Super Heavy after the first flight, as an external observer might think, no special measures were taken to suppress Pogo, and moreover SpaceX was made even no mention of this phenomenon.

Besides, during two static tests of the engines at the starting position of new Super Heavy (B9), for a very short time engine failures continued to occur, just as before [2]. At the same time, the performance of B9 on November 18 in the acceleration part of trajectory was almost ideal for an external observer, with the exception of a single moment that can be identified from the acceleration graph.

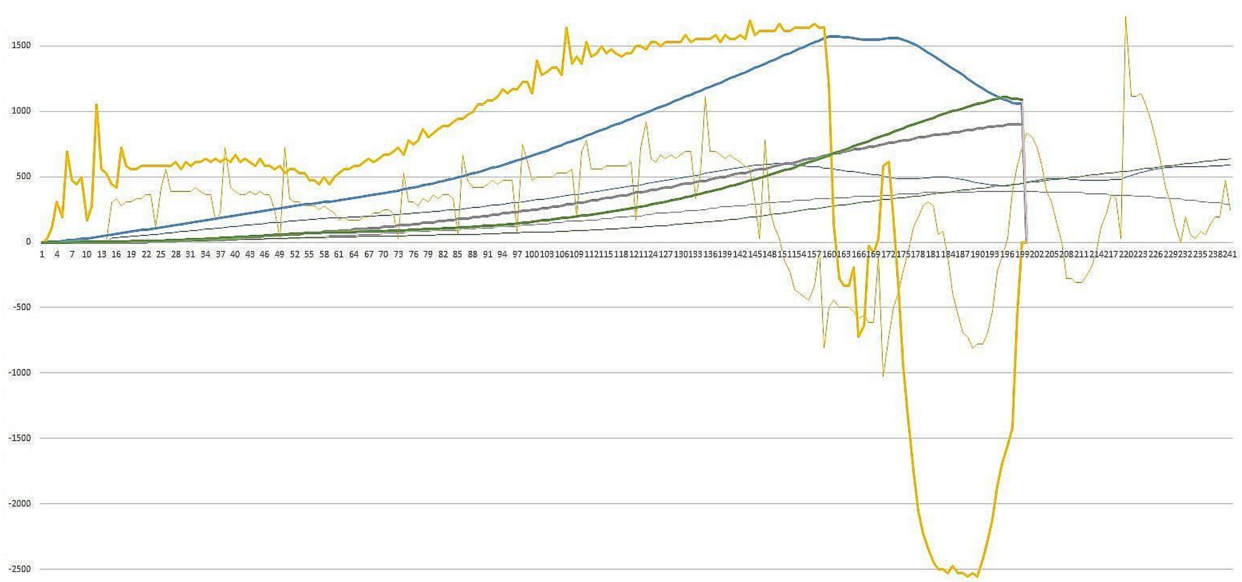


Fig. 1 – Acceleration, speed, altitude and range of Starship in the first and second flights [7]

This is demonstrated in Fig. 1 (see [7]), where a comparison was made over time (in seconds) of four Starship parameters in two flights, namely: rocket acceleration (in cm/s^2), speed (in m/s), altitude (in hm), as well as direct (horizontal) flight range (also in hm). Data related to the second flight (IFT-2) is displayed with thick lines, and data related to the first flight (IFT-1) is displayed with thin lines. Acceleration is shown with yellow curves, speed with blue lines, altitude with olive lines, and range with purple lines.

The most informative curves for finding out the answer to the question asked are acceleration graphs. They are the ones that reflect the current state of the systems, and all the rest are one or another first or second integrals of the acceleration function. It can be seen that Starship acceleration level in the second flight was initially approximately 1.5 times higher than in the first, and by the end of the acceleration phase this ratio increases to 2.5 times. The reason for these differences is essentially also shown in the figure – these are so-called superspikes, narrow peaks of first a sharp decrease in acceleration to almost 0, and then its sharp increase. During IFT-1, they were allowing the engines of the first stage from developing the necessary thrust, and also were causing them to shut down. Before the complete loss of stability and controllability on B7, up to 8 out of 33 engines turned off completely or almost completely [1]. And these superspikes themselves arose due to the interaction of longitudinal self-oscillations of Pogo-type with control system, which tried to suppress these oscillations by reducing thrust [1].

Now we are interested in relatively regular parts of the trajectories corresponding to acceleration zones of the rocket system – this is approximately the first 145 seconds for IFT-1 and 160 seconds for IFT-2. It can be seen that superspikes disappeared in the second flight, but a phenomenon similar to them, but somewhat less clearly expressed, arose at the very beginning of acceleration. Then these oscillations spontaneously died out.

If superspikes appeared due to attempts by B7 control system to suppress Pogo-type self-oscillations growing over time due to multiplicity of the hydroacoustic disturbances' frequency in the supply system to the frequency of own oscillations of the rocket hull [1], then their disappearance in the absence of any significant actions on the propellant supply lines means that in preparation for the second flight the own frequency of the hull vibrations was changed.

Have any actions been taken that could affect it? Yes they were. A month and a half after IFT-1, E. Musk, head of SpaceX, made at first glance a rather unmotivated, if not strange, decision to switch to hot stage separation, that is, to start the second stage engines even before its separation from the first stage without completely shutting down its engines. This solution was presented as a way to reduce gravitational losses and, as a result, increase the payload launched by Starship. It seemed completely premature to set such a goal immediately after first unsuccessful launch at early phase of testing essentially only prototypes of rocket system. Moreover, hot separation is clearly dangerous for reusable complex, which Starship should become in the future.

However, if we assume that the real purpose of these actions was to disrupt the positive feedback between two oscillatory circuits, then they become completely rational and even simply necessary right here and now. To achieve hot separation between stages, a special design called Forward Heat Shield Interstage (FHSI) was introduced; see Fig. 2 [8].

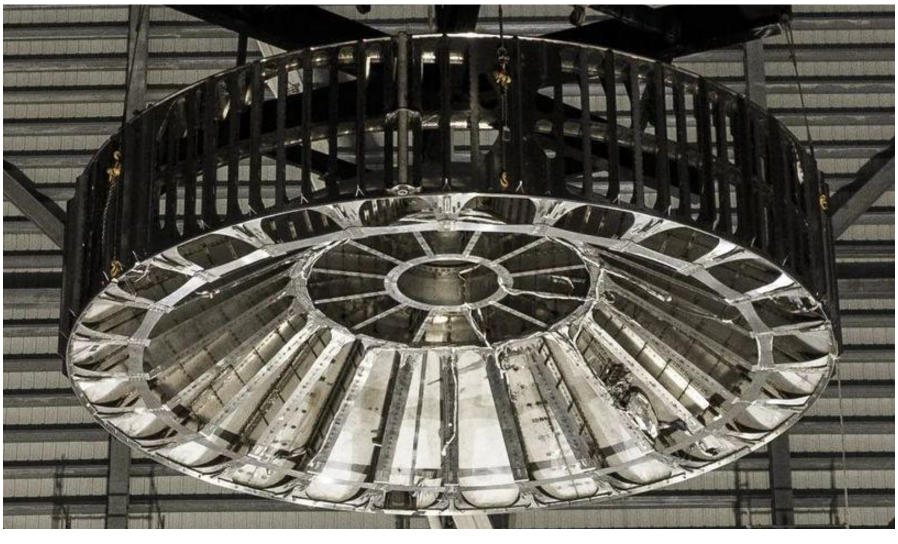


Fig. 2 – Intermediate interstage compartment or Forward Heat Shield Interstage (FHSI)

Since Pogo is the result of the interaction between two oscillatory processes with close or almost multiple frequencies, their connection can be disrupted by changing the frequency of one of these processes. Previously, in the fight against Pogo they usually influenced the hydroacoustic frequency using various hydraulic dampers or something similar (that is, including Helmholtz resonators in the oscillatory circuit) or injection of helium into the propellant supply line [9]. These are the most effective and economical ways to suppress Pogo. However, due to the fact that SpaceX still does not know methods for theoretically calculating the frequency of hydroacoustic oscillations in the propellant supply lines of rockets with large pressure drops inside them, they would have to experimentally work out all this on various scale models, spending quite a lot of time. For example, during the most acute period of the "lunar race", a relatively weakly expressed Pogo on Saturn V rocket in 1968 was suppressed by injecting helium into the oxygen supply line of the engines in 8.5 months of work, with available then huge experimental base of NASA and with the skills required which by that time NASA had already received on Titan II GLV project [10].

SpaceX has nothing similar now, not even close. Moreover, after the first flight, E. Musk announced a second launch in 1.5 – 2 months. In addition, in our time, methods for calculating vibrations of elastic structures are well developed, which, of course, are widely used in the development of Starship system. So it turned out to be possible to quickly calculate the own frequency of the rocket hull, changed by the introduction of an intermediate compartment, and to design and build this compartment in a short time. And this, by the way, completely fits into the usual working methods of SpaceX. Thus, under the guise of a struggle for efficiency, a vital operation was carried out to combat an unnamed threat to the very existence of Starship project – very intense self-oscillations of Pogo-type in the first stage, at a time when it is a single assembly with the second stage.

It can be noted that this is a typical technique of E. Musk to switch the attention of outside world from real problems of SpaceX to its future achievements. And now, in the first days after IFT-2, he talks more about a new improved version of the system called Starship V2 with Raptor-3 engines than about the results of the past test (see, for example, [11]). And this means that now he doesn’t know how to solve the problems identified in IFT-2. And it seems he stopped talking about third test launch before the end of this year.

At the same time, as can be seen from Fig. 1, the fight against Pogo in the assembly was crowned with success – such visible manifestations of Pogo as superspikes, which were observed in IFT-1, no longer exist in IFT-2. Overall, starting from the 18th second, the acceleration curve of Starship on November 18 looked quite acceptable. Except that somewhere around the 105th second there was a rather noticeable splash, but it immediately went out. It apparently could just be a failure of acceleration sensor.

However, path chosen by SpaceX, although it gave immediate results, apparently turned out to be a road to nowhere, which, it seems, E. Musk himself has finally begun to understand. The rocket has only one hull, and it is possible to replace its own frequency with inserts, but only with another fixed one. And from the hydroacoustic side, a whole orchestra plays in favor of Pogo. Firstly, in rockets with liquid rocket engines there are always 2 potential hydroacoustic oscillatory circuits – fuel and oxidizer. Second, on multi-engine rockets like Starship, different groups of engines may have slightly different lengths for different propellant supply line configurations, which mean there may be multiple oscillating circuits with slightly different frequencies. Thirdly, due to the reusability of Starship, there was a requirement to create Raptor-2/3 rocket engines with the highest performances. They have record pressures in the combustion chamber, and, therefore, record pressure drops at the pump. In addition, they also have an unusually wide range of operating thrusts, and, accordingly, pressures. And as the theory created in May of this year after IFT-1 shows, at high pressure drops in the pump, the frequency of hydroacoustic oscillations is approximately inversely proportional to the square root of the pressure drop. Thus, with a strong variation in engine thrust, the frequency of hydroacoustic oscillations also changes significantly. Fourthly, Pogo can occur not only when hydroacoustic and "elastic" frequencies resonate, but also when there is a multiplicity, which increases the number of possible dangerous oscillatory modes by at least 3 times. Fifthly, reusable stages must operate without Pogo and during their individual return, when the role of the interstage insert is reset to zero, and the frequencies of own elastic oscillations become completely different than during the acceleration of rocket stages in the assembly.

Thus, this orchestra is not just played in favor of Pogo; due to the reusability of Starship, real virtuosos with a very wide range of their playing grow up there. And the more perfect the rocket system, the higher the characteristics of its engines, the more requirements are placed on the system in order for it to be reusable, the more virtuoso their game becomes. Let's see what first flights of Starship V2 show. And it becomes impossible to resist all of them using a tool that can only change the own frequency of elastic vibrations once. In fact, this is what the IFT-2 experiment demonstrated. Now let's look at its results more carefully.

III. What new orchestra members did Starship introduce instead of previous one, muffled by the interstage compartment?

In the second flight, on the acceleration trajectory part of B9 first stage, self-oscillations that occurred in B7 stage and were caused by the interaction of disturbances in the methane supply line to the engine with a frequency of about 2 Hz and elastic oscillations of the hull with a frequency of about 6 Hz were suppressed [1]. In this case, the frequency of elastic vibrations was assessed for both stages as a single whole – Starship system. However, the analysis showed that introduction of an intermediate compartment leads to the fact that in frequency estimates it is now advisable to consider elastic oscillatory circuits within individual stages. In fact, mass of the intermediate compartment is 9.0 tons, while a ring from wall of a B7 or B9 tank of the same height (2 m) with a lid would be almost 2.5 times lighter than this compartment. Conditional average thickness of this structure made of high-strength stainless steel turns out, in this case, to be close to 10 mm, which, for example, exceeds the thickness of the armor of modern armored personnel carriers, for example, BTR-80, everywhere except its forehead, and only there the armor becomes the same thickness as this structure [12]. As far as author knows, a design of such massiveness and rigidity has appeared in rocket technology for the first time in 90 years of its existence. You can recall, for example, that in Atlas rocket the thickness of upper part of load-bearing tank was 27 (!) times smaller, see [13]. This means that the compartment is a much more rigid structure than the walls of any load-bearing tanks that are rocket hulls, including Starship system. Therefore, the intermediate compartment divides previously single oscillatory circuit into two parts.

As before, we apply the formula obtained from dimensional considerations to recalculate the frequency of elastic vibrations f_e from known rockets for any objects that are structurally close to pipes [1]:

$$f_e = \kappa \sqrt{\frac{\pi E D \delta}{mL}}, \qquad (1)$$

where κ is the proportionality coefficient, according to experimental data, of the order of 1, E is the elastic modulus of material, D is the diameter of stage, δ is thickness of its wall, m is the mass of stage, L is its length. In this case, the proportionality coefficient κ is determined from known data of Saturn V and Titan II GLV rockets. For Saturn V-scale rockets and stages, the proportionality coefficient turned out to be very close to 1 – $\kappa \approx 1.0$ [1].

However, now, as will be seen from what follows, we will need estimates of the own frequencies of individual stages of Starship, including for conditions when they had very little propellant. And their mass turned out to be less than Saturn V in some cases by almost an order of magnitude. And all these correlation relationships like formula (1) can give acceptable accuracy, usually only in those cases when the main parameters of the calculated object, and first of all its scale, don't differ too much from similar parameters of prototype. Therefore, another much smaller rocket was evaluated, also having essentially the same tube design as Saturn V or Starship, and which also exhibited pronounced Pogo oscillations. The own vibration frequencies of its hull turned out to be known, while its mass was 20 times less than Saturn V rocket. It was a variant of combat rocket used to launch Gemini manned spacecraft – Titan II GLV.

Data were obtained from sources [14 – 16], which, using formula (1), made it possible to estimate the calculated frequency of its own oscillations – 19.8 Hz. During flights, Pogo frequencies of up to 13 Hz were recorded [9]. Thus, the proportionality coefficient κ in formula (1) for the case of a relatively small rocket should have been about 0.65. To estimate the own frequencies of Starship stages in those calculated cases when their mass m was significantly less than the launch mass m_0 of Saturn V rocket, a power-law interpolation of this coefficient was used:

$$\kappa \approx (m/m_0)^{0.145}$$

Now let's try to explain the passage of the main critical processes during the second test flight of Starship in assembly of the first stage B9 and the second S25, that is, during IFT-2. Own frequencies f_e of Starship during IFT-1 (B7+S24) were estimated in the range of 5.8 – 6.25 Hz [1]. Own frequencies f_e of the first stages B7 and B9 during ground tests, according to estimates carried out for them, turned out to be in the range of 9.65 – 9.8 Hz due to their lower mass and shorter design length than that of the system in total [2].

With IFT-2, unlike IFT-1, even during flight in the assembly, the own frequencies of both stages were estimated separately. The only difference between the calculation at the launch for IFT-2 and what was carried out in paper [2] during ground tests was that in the second flight the total mass of the system was substituted into formula (1) – 5.0 kt, and not the mass of its first stage – 3.6 kt, since during flight the second stage was on top in the form of a load. Then the own frequency of B9 in this calculated case became equal to f_e = 8.2 – 8.3 Hz.

Oscillations of the first stage from the operating engines were transmitted through a rigid intermediate compartment to the second stage, and oscillations with their own frequency should also be excited in it. It was estimated using formula (1) with its estimated length $L \approx 45$ m and mass m = 1.4 kt (see [1]). With a proportionality coefficient for this mass $\kappa \approx 0.9$, the frequency turned out to be the following – f_e = 14.5 – 16.8 Hz, almost twice as high as that of the first stage. In this case, two bodies oscillating at fairly close frequencies, influencing each other, create a complex non-harmonic oscillation of the beat type, which is described by a carrier frequency equal to half the sum of their own frequencies (f_e = 11.5 – 12.5 Hz), and an envelope superimposed on the carrier with the frequency of their half-difference (f_e = 3 – 4 Hz).

Now let’s compare the frequency of the carrier component of these elastic oscillations of Starship system with the frequencies of possible hydroacoustic disturbances of its first stage propellant supply system, described in detail in paper [1]. It immediately becomes clear that, unlike IFT-1, the frequency of hydroacoustic oscillations in the methane supply line of the engines is too low to initiate Pogo process in this situation. But the spectrum of the corresponding frequencies in the oxygen supply line, which covers the frequency band from approximately 9 – 12 Hz to 18 – 23 Hz (depending on the exact lengths of the supply pipelines) is quite suitable for resonance with the frequency of carrier component of the elastic oscillations, see table 1 from papers [1, 2].

In it, c is the speed of sound in liquid cryogenic oxygen, p_2/p_1 is the degree of pressure increase (or drop) in the oxygen pump of Raptor-2 engine, L_1 is the length of the oxygen path from the pump to gas generator, L_2 is the length of the oxygen path from tank to the pump, L_3 is their sum, L_{eq} is the effective length of the oscillatory circuit, that is, the length that corresponds to the frequency of oscillations that occur in it in the absence of a pump, f_n is the frequency of hydroacoustic oscillations of liquid oxygen in the line. Due to the author’s lack of accurate data on the lengths of sections of the oxygen line, calculations were carried out for three variants of its design. The operating pressure drop on the pump is $p_2/p_1 = 170$, the other two values correspond to two levels of thrust throttling, and the smallest value refers to the minimum thrust mode of Raptor-2 engine, which is 20 % of the nominal value, that is, it is the lower limit of the operating mode [1].

Table 1

Rocket Stage Engine	**p_2/p_1**	**L_1 (m)**	**L_2 (m)**	**L_3 (v)**	**L_{eq} (m)**	**f_n (Hz)**
c = 930 m/s						
Starship Super Heavy Raptor-2	170	0.30	3.00	3.30	19.6	*11.9*
	85				14.0	16.6
	42.5				10.1	23.0
	170	0.40		3.40	22.6	**10.3**
	85				16.1	14.4
	42.5				11.6	20.1
	170	0.50		3.50	25.2	**9.21**
	85				18.0	12.9
	42.5				12.8	18.2

From all of the above, it follows that after turning on the engines, shortly before reaching the nominal thrust mode, the frequencies of two oscillatory processes coincided, which caused the occurrence of Pogo. But a further increase in thrust brought the hydroacoustic frequency out of resonance, and Pogo process died out. This is exactly what we see in Fig. 1 in a period of 4 – 18 seconds – a powerful burst of oscillations, which also quickly faded after the acceleration reached stationary values, and, therefore, the engines reached the nominal operating mode. But with some changes in the basic parameters of Starship system, it may turn out that when it reaches a stationary mode, Pogo won’t stop. Then one would expect the rocket to collapse directly on launch position. And who knows what Starship V2 system will have on this mode?

Thus, having damped the source of Pogo excitation through hydroacoustic oscillations in the methane line of the supply system, the intermediate interstage compartment generated a new Pogo exciter, no longer with a multiplicity of 3, but a resonant one (that is, with a multiplicity 1), and, therefore, potentially even more dangerous.

Let’s now consider the second possible situation with the excitation of Pogo on B9 first stage at the moment of restarting the inner ring engines during its boostback maneuver. According to the iconography from IFT-2 video [3], it follows that by that time about 12 % of the propellant remained in the stage, and stage mass at this moment can be estimated at 0.6 kt. The proportionality coefficient κ for such a mass is estimated at $\kappa = 0.79$, and it follows from formula (1) that in this episode the own frequency of elastic oscillations of B9 stage is approximately the following – $f_e = 18.4 – 18.7$ Hz. Analyzing the corresponding hydroacoustic frequencies, we can see that resonance in this case occurs at significantly lower pressures on the pump, and, therefore, at engine thrust much lower than the nominal one and even below 50 %, and in the last version from Table 1, they reach to the lower limits of the engines’ working area. So the brief splash of Pogo when the engines restarted was apparently relatively weak due to the fact that the thrust was not very high or multiplicity of frequency did manifest itself there again.

And engine failure at this moment could probably be caused by loss of fuel supply to the engines due to the occurrence of alternating and rapidly changing overloads during the first stage braking maneuver. It should be taken into account that in Fig. 1, all accelerations are presented in the original coordinate system, but at a time interval of approximately 170 – 180 seconds, the first stage rotated around its transverse axis by 180°, and in its coordinate system, accelerations and overloads changed signs.

At the same time, 9 out of 10 inner ring engines were turned on from 169 to 170 seconds at the moment of almost zero acceleration of the stage and at the moment of its "direct" position. Shutdown of the first 3 of the 12 operating engines occurred during in 4 seconds from 174 to 178 during the turn of the stage, starting with one of the central ones, which operated without stopping from the very start. At this time, as the engines were reaching the design mode, there was a rapid increase in overloads, after which a stationary mode of braking began, lasting 8 – 9 seconds, but then in 6 seconds, from 191 to 197, all the remaining 9 engines switched off.

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

Thus, zone of negative accelerations shown in Fig. 1 from 173 to 199 seconds, was in fact a zone of large positive accelerations caused by the engines working to brake an almost empty stage. Moreover, their operating conditions were quite normal – fuel was very tightly pressed to bottom of tanks, and the stage had already started more or less straight flight with an approximately constant overload of +2.5 g. In general, this differed little from the flight mode that successfully completed just 20 seconds before. However, after 8 – 9 seconds, the 9 remaining engines by that time suddenly began to quickly turn off one after another, seemingly already under normal operating conditions, and when the last one turned off, an explosion and destruction of stage B9 occurred, see Fig. 3, showing what was visible in the sky at 201 seconds [3]. This is all very similar to the fast-paced Pogo excitement.

IV. What was the reason for the destruction of S25 stage on the second flight of Starship?

It remains to answer the third question: "Why, without any apparent reason, at the end of the acceleration phase did all the second stage engines suddenly switch off after their long and stable operation?" In Fig. 4 we can see a reflection of this situation on the iconography from IFT-2 video – at the time of 00:08:03, 30 seconds before the planned shutdown, all 6 engines are working, which they have been doing for 322 seconds without any problems, and at 00:08 :04 they all suddenly switched off [3]. After this, one could observe a rather transparent, but still clearly visible plume spreading in the sky, indicating the destruction that occurred on board the second stage, which led to the release of propellant components.

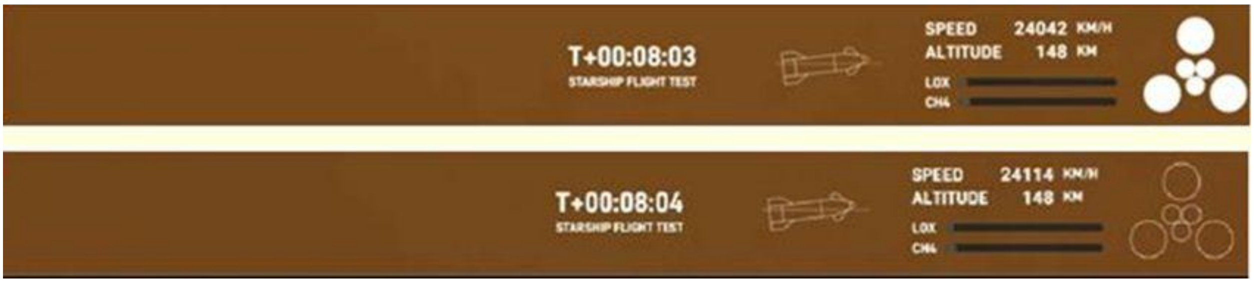


Fig. 4 – Switching off the second stage engines

Let us estimate the frequencies of accompanying processes that generate Pogo. According to the iconography in S25, before this event, about 14 – 15 % of the propellant remained, and with a dry mass of the stage of 0.15 – 0.18 kt, its total mass was about 0.325 – 0.365 kt, κ ≈ 0.725 – 0.75, and the own frequency at this moment can be estimated approximately like f_e = 24 – 27 Hz. If the lengths of the oxygen lines supplying the engines at the second stage are close to those at the first stage, then as a first approximation, the data from Table 1 can again be used to estimate hydroacoustic frequencies. Then, with a multiplicity of 2, the exciting frequency of hydroacoustic oscillations will be equal to 12 – 13.5 Hz, which is quite close to the first case of the occurrence of a strong splash of vibrations at the start of Starship discussed above (f_e = 11.5 – 12.5 Hz).

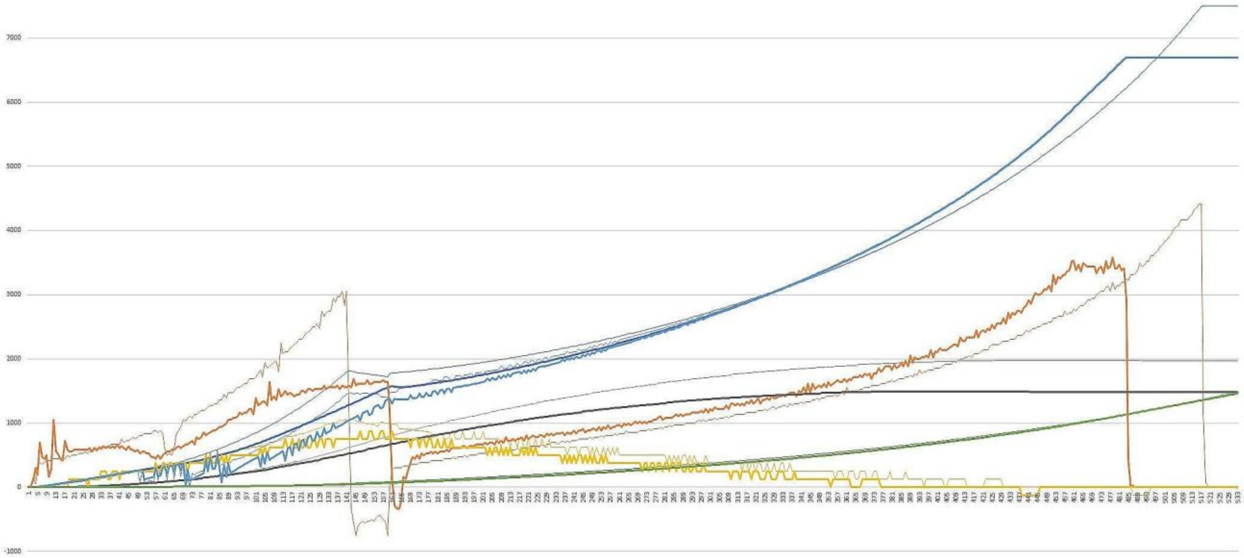
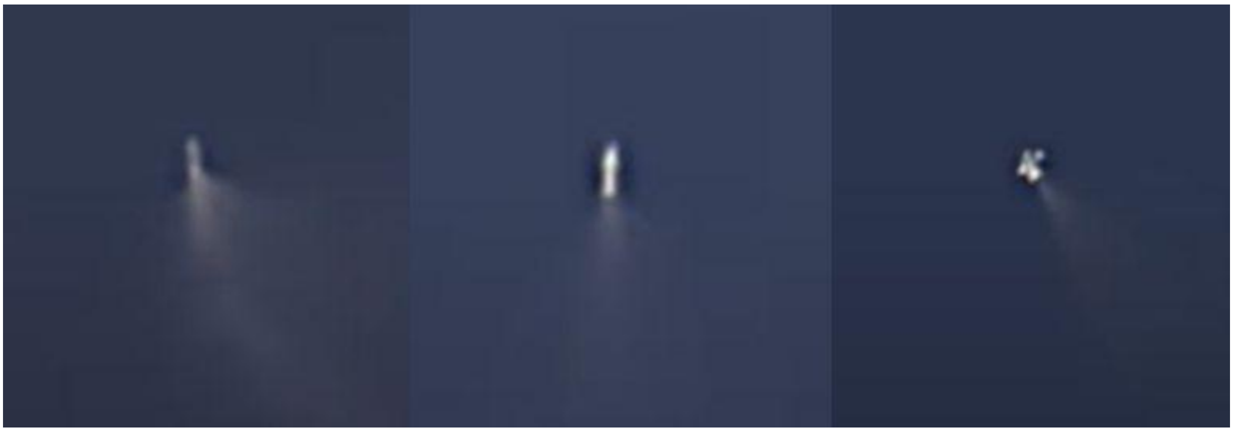


Fig. 5 – Acceleration, speed, altitude, direct range, as well as horizontal and vertical velocities of Starship in the second flight in comparison with similar parameters of Falcon-9 rocket [7]

From the point of view of static analysis, these 2 incidents of Pogo excitation are quite close to each other. Generalizing a little, and taking into account the relatively low accuracy of own frequencies estimates, we can say that in both of them f_e = 12.5 ± 1.0 Hz, and in the first case resonance, and in the second coincidence of frequencies with a multiplicity of 2, occurred at approximately the same thrust level of each engine Raptor-2 (in the first incident there were 33 of them, and in the second – 6). But there was a significant difference in the dynamics: at the start of Starship, the engines abruptly jumped through intermediate modes and quickly reached the nominal operating mode, where there was no longer resonance with elastic vibrations. Pogo simply did not have enough time to fully develop. And in the second case, from the moment of 00:07:40, throttling of the second stage engines began so that its acceleration did not exceed 3.5 g – apparently, such a limitation was built into the control system, see Fig. 5 [7] (This figure is, in principle, similar to Fig. 1, and differs from it only in that the characteristics of Starship are shown up to the end of the termination of telemetry transmission from the second stage, Falcon-9 rocket is the object of comparison here, and also in that the direct range here measured in kilometers).

Due to limits of acceleration of the second stage, the thrust of its engines slowly and gradually decreased. At the same time, the pressure in the combustion chamber decreased also and the frequency of hydroacoustic disturbances increased (see Table 1). Initially, at the nominal operating mode of the engines, their frequency was most likely in the range of 9 – 10.5 Hz, and was more than 2 times lower than the own frequency. But, gradually, it approached (taking into account the factor of 2) the own frequency of vibrations of the hull, Pogo process began, and at least one of the oxygen supply pipelines to the engine was destroyed. After this, explosive cascade destruction began in the engines, a loss of power occurred, and all devices and instruments on the stage failed. However, judging by a video made using a telescope by an amateur astronomer from Florida [5], construction of S25 remained mostly whole for at least 64 seconds, see Fig. 6. On it, frame a) was taken at 00:08:45 after the start (42 seconds after the accident), frame b) – 00:08:56, 11 seconds after the first, and frame c) – 00:09:07, another 11 seconds later.



a) **b)** **c)**

Fig. 6 – Three shots of S25 after the accident from Florida's video

Frame b) clearly shows that S25 has generally retained its basic proportions, especially considering that it is not exactly perpendicular to the line of sight. The maximum that it could lose, if at the time of 00:08:03 there was, after all, a fairly strong explosion, was the aft engine compartment. In the last available frame, S25 appears to begin to fall apart into pieces, which soon fell into the ocean near the island of Puerto Rico. However, all these details are no longer of particular interest for investigating the cause of S25 incident.

To complete the picture, it remains to briefly consider the hot launch of the second stage. With its starting mass of about 1.4 kt, the proportionality coefficient κ in formula (1) is close to 0.9. Then an estimate of its own frequency gives the values $f_e = 14.5 – 16.8$, which is quite close to the case of restarting the first stage engines after separation ($f_e = 16.6 – 16.9$ Hz). The greater scatter in estimates of the frequency of the second stage is due to the fact that the author doesn't know what the current thickness of its wall is – 3 or 4 mm (see [1]). But, however, as before, these 2 cases can again be reduced together to a situation with an own frequency $f_e = 15.5 \pm 1.0$ Hz. At such frequencies, resonance with hydroacoustic disturbances occurs when the engine thrust is less than 50 % of the nominal (see Table 1), and Pogo process develops relatively slowly. And in both cases there should have been a rapid increase in thrust. When starting the second stage engines, everything seemed to go smoothly due to fast pass through the resonance mode. The same should have happened when the first stage engines were restarted, but here additional factors obviously intervened, associated with a fast changing large negative overload.

Conclusions

1. Although the method of recalculating the frequency of elastic oscillations of rockets from the prototype neglects most of the design features and, as a result, is relatively inaccurate, nevertheless, together with the method of calculating hydroacoustic oscillations under strong pressure drops, it led to the construction of pictures of the main transition processes that are completely consistent with how Starship actually behaved in configurations B7, B7+S24, B9+S25, as well as B9 and S25, in two flights and in three ground tests.
2. An explanation is given of how the introduction of intermediate interstage hot separation compartment suppressed the oscillation process on B9 stage in the second flight of Starship, which led in the first flight with B7 stage to a rocket crash.
3. It has been shown that at the same time the presence of this compartment ensured the emergence in the first stage of rocket a potentially even more dangerous oscillatory process of Pogo-type with a different frequency.
4. It was also demonstrated that the cause of the second stage failure in the second flight at the end of the active operating mode was caused by the occurrence of Pogo when throttling its engines.
5. The absence of problems with second stage in-flight launch demonstrated in actual flight is shown to be consistent with estimates based on the use of the theory described here.
6. Estimates also show that the connection between the explosion of the first stage in the second flight during a boostback and self-oscillations of Pogo-type could well have occurred due to rapid changes in its flight conditions.
7. Proposed in the paper [1] method for calculating hydroacoustic oscillations in supply systems for liquid rocket engines with propellant components with large pressure drops allows in advance, before flight experiments, to quickly and easily detect and suppress manifestations of potentially dangerous combinations of technical characteristics of both the rockets themselves and their propulsion systems that can cause destructive self-oscillations in flight, including catastrophic ones.

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