Paradox of Starship two flights and its resolution

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Because (not to speak of greater numbers) even two articles of circumstantial evidence – though each taken by itself weigh but as a feather, – join them together, you will find them pressing on the delinquent with the weight of a millstone.
J. Bentham

Summary

It's shown that all 3 cases of excitation of Pogo type self-oscillations identified in Starship second flight, 2 of which led to explosions of both stages of this system, were overcome in its third flight. This was done through precise and strictly controlled changes in its power plant operation. But at the same time, no attempts were made to prevent of Pogo process that newly appeared and also ended in an explosion in a previously untested flight mode – landing of the first stage. From this it is concluded that when changing the power plant control algorithms, previously obtained experimental "pre-emergency" data and recalculation of hydroacoustic oscillations frequencies by engine operating modes were used. The frequency conversion formula was derived in Pogo theory created by author of this work in the spring – summer of 2023, and became limitedly available to SpaceX no later than December 2023.

Evidence is provided that in the period from the beginning of October 2023 to the end of January 2024, no less than five public and business structures attempted to block information about this theory. However, in February – early March 2024, SpaceX applied the corollaries of Pogo theory available to it to change the operating algorithms of the power plant, thus ensuring that Starship successfully passed in the third flight those modes that ended in explosions in the second flight.

The conclusion is drown that without full use of Pogo type self-oscillations theory, SpaceX will be forced to sequentially go from one accident to another, experimentally identifying all possible cases of Pogo for which Starship system is a natural habitat. This will continue to happen as new versions of the rocket system are transitioned, turning their development into an endless series of unexpected accidents, and may lead to the exhaustion of resources available to SpaceX to continue this exciting process.

Key words: *Pogo, self-oscillations, accident, Starship, frequency, excitation, hydroacoustic oscillations, own oscillations, boostback, landing*

Symbol list

c – speed of sound
f_e – own frequency of rocket hull
f_n – frequency of hydroacoustic oscillations
h – height
L – length
L_{eq} – equivalent length of oscillatory circuit
p – pressure
v – speed
w – acceleration

I. Introduction

Second flight of Starship (IFT-2), which took place on November 18, 2023, was completely successful until the return maneuver (boostback) of the first stage (Super Heavy B9 booster), as well as until the release of boost gases from the second (Ship S25) at the end of its acceleration, but it ended, however, with explosions of both stages [1 – 3]. 4 months after it, on March 14, 2024, the next, third flight of the rocket system (OFT-3) was carried out, in which these 2 critical points were successfully passed, but, nevertheless, during the third, last ignition of the first stage engines, necessary for a soft landing on the water surface, an explosion occurred again, destroying, as before, the booster on the last kilometer of its flight path. The second stage, after flying along a ballistic trajectory through half of the Earth, also collapsed upon entry at a speed close to orbital into the dense layers of the Earth's atmosphere [4].

However, issues related to the stabilization of the second stage and its control in orbit, as well as to the aerodynamics, heating and dynamics of hypersonic flight in the atmosphere are not considered here. The article is devoted exclusively to the explosive destruction of Starship stages due to the occurrence of catastrophic Pogo type self-oscillations in them [1 – 3, 5]. It should be noted that in each of the subsequent flights, starting from the second, the causes that led to explosions and destruction of the system and/or its stages in the previous flight were completely eliminated. So progress in fight against this most dangerous phenomenon is absolutely obvious. But in these new flights at newly achieved frontiers, new reasons for the appearance of Pogo arose, which again had to be overcome. And this article is devoted to explaining why this happened every time. At the same time, the main attention was focused on analyzing the results of second and third flights, since it was in the interval between them that events occurred that determined the latest successes of SpaceX in the flight testing program of Starship. But they also gave rise to new problems that could negatively affect the further development of this program.

II. Paradox which discovered during analysis of Starship first test flights

A fairly detailed identification of the reasons for the differences in the outcomes of Starship first and second flights was carried out in [1, 5]. It was shown how the introduction of an intermediate interstage compartment for hot staging suppressed in Starship second flight that Pogo type self-oscillatory process on B7 stage, which in the first flight led to an accident and explosion of the rocket during its acceleration phase [5]. The process of Pogo type self-oscillations, as is known, is excited by the proximity or multiplicity of frequencies of hydroacoustic oscillations in rocket engines supply lines of at least one of the fuel components and own elastic oscillations of its hull [6]. The insertion of the intermediate compartment changed the own frequency of elastic vibrations, and thus broke the positive feedback between these two types of fluctuations, due to which they are able to intensify until destruction of oscillatory system in which exist. Everything is logical – the frequency of one of the two interacting oscillatory processes was shifted from a multiple of the other, and they ceased to noticeably influence each other. The frequencies of both processes were measured in the first flight, and the frequency of elastic vibrations of the structure is calculated, so it was possible to understand what such a change would lead to. However, even without numerical calculations it is clear that shift in the elastic frequency will be large and Pogo will be suppressed.

Thus, the introduction of an intermediate interstage compartment for hot staging turned out to be a very successful measure, simultaneously solving two problems: suppressing Pogo process when accelerating a stack of two stages, as well as increasing the payload due to a decrease in gravitational losses during staging. Of course, this may raise the problem of reducing life of the reusable first stage due to hot staging, but before the moment when this can become relevant, many other critical problems in Starship program has to be solved.

As a result of this measure, during the second test flight, a completely unusual two-level self-oscillatory process that appeared in the first flight of the rocket system was successfully suppressed, but its creators instead unexpectedly encountered 3 new problems of a similar type. Firstly, on B9 buster, at the very start, a potentially even more dangerous Pogo type process arose. Its danger lies in the fact that the hydroacoustic component was associated with oscillations in the line of liquid oxygen with a multiplicity of 2 [1], and not liquid methane with an initial multiplicity of 3 as in the first flight [5]. In this regard, the rate of Pogo development at the start of IFT-2 was higher than during IFT-1. But, fortunately, this process began when B9 stage engines were gaining thrust, and when they reached the nominal (design) operating mode, the frequencies of hydroacoustic and elastic oscillations diverged, and Pogo process spontaneously died out [1].

Second time, Pogo process occurred on Starship first stage in the second flight when its engines were re-ignited during the return maneuver (boostback) after staging. And third case is Pogo excitation at the final stage of second stage acceleration after the release of excess boost gas from its oxygen tank. In both cases, as is known, these processes ended in spontaneous explosions of both stages. Mechanisms of these processes were described in sufficient detail in papers [1 – 3], and there is no need to repeat it here. The only important thing is that, having suppressed Pogo process that arose in the first flight, the developers of Starship unexpectedly encountered three new similar processes, the development of which was almost impossible to prevent using the previous method – introducing some changes into the design of the vehicle. In principle, it would be possible to follow the path in which similar problems were solved 50 – 65 years ago – by installing special hydraulic or gas resonator-dampers on the fuel supply lines for changing their frequency characteristics, or using helium injection for the same purpose [6, 7].

However, SpaceX in the fall of 2023 (like everyone else) wasn’t aware of methods for calculating the frequency of hydroacoustic oscillations in the fuel lines of rocket engines. Therefore, changing the frequency characteristics of fuel supply lines in such ways required a large number of experiments, including flight experiments. For example, when American rocket engineers first encountered such manifestations of Pogo that needed to be eliminated, it took Martin Company, the developer of Titan II rocket, as well as NASA and USAF almost 2 years to solve this problem. The fight against Pogo lasted 22 months – from March 1962 to January 1964, no less than 24 Titan II rockets launches were carried out until the desired result was achieved. It should be noted that, in contrast to the spontaneous explosions of Starship stages, then there were only unacceptably high vibrations of Titan II hull, and only once during this series of tests did the rocket spontaneously explode. This happened when it was possible to suppress oscillations in the oxidizer supply line, and, as a result, an unlimited increase of oscillations in the fuel supply line began [7].

But this time, on the third flight of Starship, was demonstrated that all 3 Pogo cases identified on the second flight were successfully eliminated just 4 months after the second flight. Of course, one could assume that in a company whose leaders had never officially uttered the word Pogo, a theory of this process was almost instantly created (which couldn't be done in ¾ centuries), with help of which it would be possible understand all aspects of this phenomenon. After which it would be relatively easy to quickly make the necessary design or other changes to the rocket and/or to its flight program. However, such an assumption is simply is elementary refuted by a simple consideration, against which it’s almost impossible to find any objections. With new, third activation of the same first stage engines, which by that time had already operated 2 times during acceleration and boostback without any comments, at landing stage, a spontaneous explosion of the booster again unexpectedly occurred – so where were the developers, armed with the theory that allowed quickly (in no more than 2 months) solve the 3 previous problems? After all, back on January 12, 2024, at the speech by the head of SpaceX, E. Musk, not a word was said about the problem of a booster explosion, and what was said about the explosion of the second stage fairly approximately reflected the real course of events [8].

It would seem that such a combination of events is completely impossible: either the explosions had to continue, or stop completely. That is, a seemingly logically insoluble paradox arose – the paradox of the last two flights of Starship, the second and third (IFT-2 and OFT-3). And the rest of this work is devoted to its resolution.

III. Demonstration of main parameters of Starship trajectory in the second and third flights

In source [9], shortly after the third flight, as before after the previous two, main parameters of Starship were presented based on data obtained from video stream (see [4]). In Fig. 1 system data along flight path of the first stage (booster B10) are shown, and in Fig. 2 – along the flight path of the second stage (ship S28) until the operation of its engines stops.

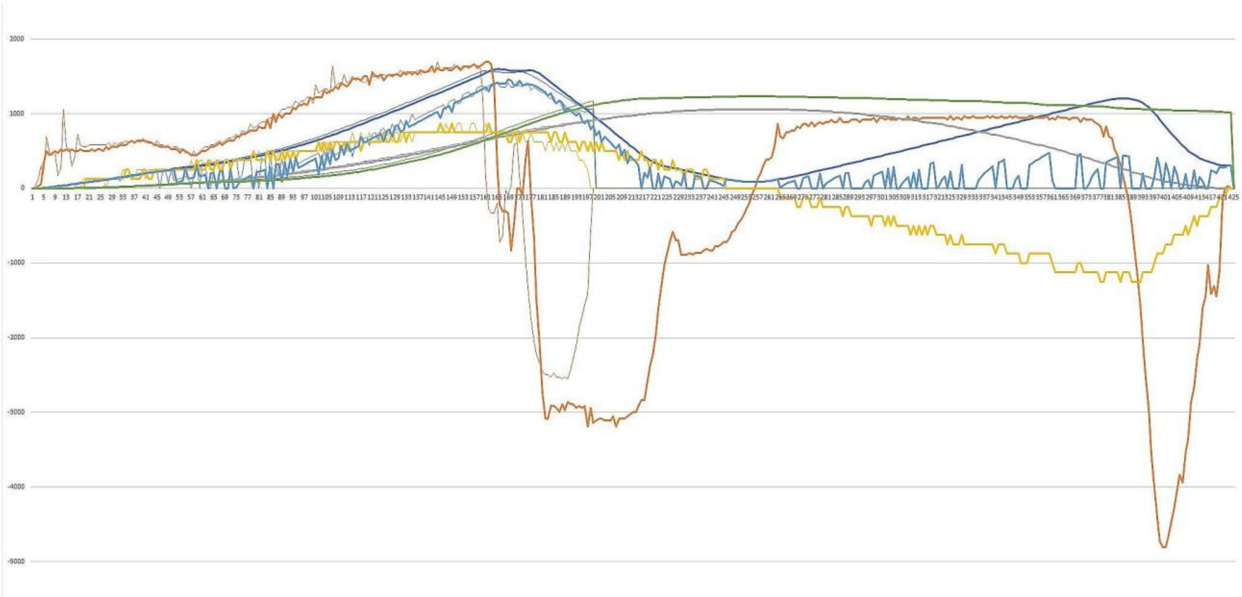


Fig. 1 – Acceleration, speed, altitude and direct (horizontal) range, as well as horizontal and vertical speed components of Starship booster in the second and third flights [9]

In Fig. 1, 2, a comparison was made in time (in seconds) of six parameters of Starship first and second stages in the second and third flights, namely: acceleration (in cm/s^2), speed (in m/s), trajectory altitude (in hundreds of meters), direct (horizontal) flight range (in thousands of meters), as well as horizontal and vertical speeds (in m/s). Data related to the third flight are displayed in thick lines, and data related to the second flight are displayed in thin lines. Acceleration is shown with purple-brown lines, speed with blue lines, and altitude and range with black lines.

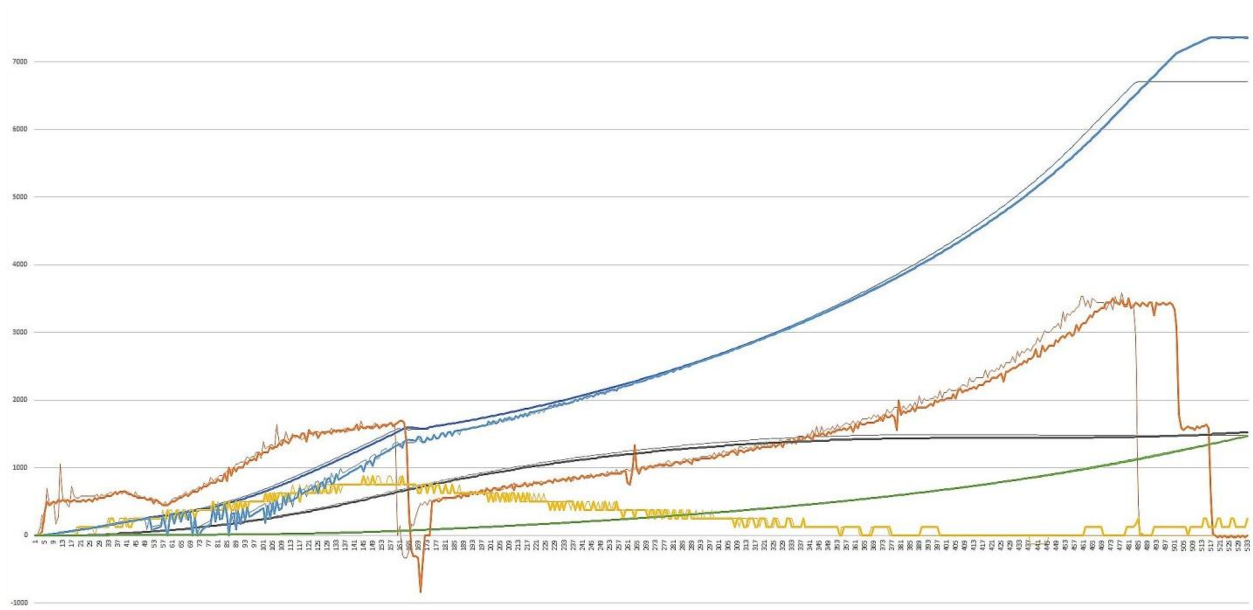


Fig. 2 – Acceleration, speed, altitude, direct range, as well as horizontal and vertical velocity components of Starship second stage in the second and third flights, including as part of stack [9]

It should be understood that the accelerations shown here are inertial without taking into account gravitational acceleration and that after staging and return maneuver, the direction of the booster's flight changed to the opposite, but algorithm by which the acceleration is calculated doesn't take this into account, and therefore buster acceleration changes sign, and after 160 – 170 seconds of flight the negative accelerations in Fig. 1 are actually positive, that is, they press fuel components to lower bottoms of tanks, which creates conditions for its normal supply to the engines. And in the interval from approximately 275th to 375th second, during free flight of the booster, under the influence of almost only gravitational forces, it is in weightlessness and the total acceleration there is close to 0.

IV. Analysis of Starship behavior during second and third flights in the vicinity of second flight's first critical point

First critical point of Starship second flight was the period of time from approximately the 4th to the 19th second, that is, on the start. At this time, the smooth and rapid increase in the rocket's acceleration stops, and up to the 19th second one can see its sharp fluctuations, more or less similar to those observed in the first flight along almost the entire trajectory, and their scale far exceeds anything that can be see further on the acceleration graph in the second flight. But these fluctuations stopped as quickly as they began. In the first half of this time interval, Raptor-2 rocket engines of the booster reached their nominal operating mode. Apparently, due to the fact that in Starship autogenous pressurization of fuel tanks (that is, combustion products from the engine gas generators are supplied to the tanks) is produced, achieving the nominal pressure in the tanks before reaching maximum thrust requires some time for the engines to operate at intermediate thrust. And the time of this process is noticeably longer than, it was for Saturn V rocket. At least judging by Fig. 1, Starship engines would reach nominal thrust in the second flight in the absence of its fluctuations by approximately the 10th second of the flight, or by the 12th second from the moment of central engines and inner ring engines start [10], while the length of this interval for Saturn V rocket was only 1.5 – 2 seconds [11].

The most natural explanation for such sharp changes in acceleration at the very beginning of the trajectory is the occurrence of Pogo type self-oscillations in Starship, the envelope of which is shown in Fig. 1 as section of the acceleration graph on the start. In order for a pogo-type process to arise, it is necessary that the frequency of hydroacoustic oscillations f_n in any of two types of fuel lines feeding the rocket engines be close to the elastic frequency f_e or a multiple of it. In paper [1], an estimate was given for the frequency of own elastic vibrations of the hull – f_e = 11.5 – 12.5 Hz. As a first approximation, we will take the average value f_e = 12.0 Hz, and, as usual, we will assume that Pogo can occur if hydroacoustic frequencies deviate from this value by no more than 8.5% [5]. Then the dangerous frequency range is $11.0 < f_n < 13.0$ (Hz).

For three variants of these supply lines geometry, the frequency of hydroacoustic oscillations in the oxygen line when Raptor-2 engines operate at nominal mode (with a pressure ratio on the oxygen pump $p_2/p_1 \approx 170$) with the oxygen supply line lengths indicated in Table 1 can be in the range f_e = 10.2 – 10.3 Hz, see Table 1, which is outside the frequency range of elastic vibrations.

Table 1

Rocket Stage Engine	p_2/p_1	L_1 (m)	L_2 (m)	L_3 (m)	L_{eq} (m)	f_n (Hz)
c = 930 m/s						
Starship Super Heavy Raptor-2	170	0.30	4.00	4.30	22.7	10.2
	135				20.3	**11.4**
	160				22.1	10.5
	170	0.40	3.00	3.40	22.6	10.3
	135				20.2	**11.5**
	160				21.9	10.6
	170	0.45	2.70	3.15	22.7	10.2
	135				20.3	**11.5**
	160				22.0	10.5

The following notations are used in Table 1: c is the speed of sound in liquid cryogenic oxygen, p_2/p_1 is degree of pressure increase in Raptor-2 oxygen pump, L_1 is length of the oxygen path from the pump to the gas generator, L_2 is length of the oxygen path from the 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 final section of time interval for Raptor-2 engines to gain full thrust, the pressure in their main combustion chamber increases to the nominal value. At the same time, the pressure drop across the oxygen pump increases to the nominal value – a parameter that greatly influences the frequency of hydroacoustic oscillations. And the higher the drop, the lower the frequency of these oscillations. For the first time, signs of Pogo in the second flight appeared approximately at the 4th second of the flight at Starship acceleration of 2.5 – 3 m/s^2, and fully stopped at the 22nd second, when the acceleration of the vehicle became at least 6.5 m/s^2. Thus, even taking into account some reduction in mass, the appearance of Pogo occurred at thrust of about 0.8 of the nominal (taking into account ~ 10 m/s^2 gravitational acceleration). This mode corresponds to a pressure drop across the oxygen pump of about 135, which increases the frequency of hydroacoustic oscillations by about 12 %, see Table 1.

In this case, the frequency can be quite close to the frequency of elastic vibrations of the rocket hull (see calculation options with p_2/p_1 = 135), which should cause the appearance and growth of Pogo. However, an increase in engine thrust and pressure in its main combustion chamber soon leads to a divergence of frequencies, and Pogo spontaneously goes out. Thus, such a model explains both the occurrence of these self-oscillations and their cessation at the start of the second flight of Starship. This process, fortunately, simply didn't have time to develop to a dangerous or even catastrophic level, which then happened twice on the second flight later. This was written about in article [1] at the very beginning of December 2023, 2 weeks after the second flight.

What can now be seen on this part of the trajectory during the third flight? Firstly, Pogo oscillations have disappeared, see Fig. 1. Secondly, the rate at which the power plant reached the nominal thrust mode was changed, which manifested itself in a change in the rate of increase in rocket acceleration in the first seconds of flight. The entire section of dangerous modes was covered in approximately 3 seconds, from 4th to 7th, that is, no less than 2 times faster than in the second flight – from 2nd to 9th – 10th seconds. This happened because in the third flight the rapid increase in thrust began 2 seconds later than in the second and ended earlier with the engines reaching a quasi-stationary mode of operation with a total thrust 5 percent below the nominal one. Only further, at about the 35th second, the accelerations, and, therefore, the thrusts of the power plants of boosters B10 and B9 became equal. The fact that the rapid acceleration of B10 booster engines ended at a thrust level of about 95 % of nominal thrust didn't play any noticeable role. In this mode, the pressure drop across the oxygen pump was $p_2/p_1 \approx 160$, the frequencies of hydroacoustic oscillations were only 3 % higher than in the nominal mode, and, obviously, had already noticeably deviated from the resonant values. At the same time, the stationary mode of engine operation is more stable than the transient mode, therefore the obvious desire to quickly pass through the engine operating mode in which Pogo is excited led to such a change in the thrust control program. Although, perhaps, a slightly lower acceleration at the end of the transition mode of engine operation was simply due to the fact that launch mass of Starship in the third flight was slightly greater than in the second. But, in any case, the result was excellent – the first critical point of November flight was passed quickly this time without any problems.

V. Analysis of Starship behavior during second and third flights in the vicinity of second flight's second critical point

The second critical point of Starship second flight was short period during which its first stage performed an active maneuver to turn around and enter return trajectory (boostback). During its implementation, three constantly running central engines, after being switched on again, were to be joined by 10 more engines of the inner ring. In reality, in a time interval of approximately 170 – 180 seconds, the first stage rotated around its transverse axis by 180°, while 9 out of 10 engines turned on, and then during the time from the 174th to the 178th seconds 3 of 12 operated engines stopped working. However, the turn of the stage was completed, and from approximately the 180th second it continued braking in a quasi-stationary mode, already in a horizontal position of buster with a constant acceleration $w \approx 25$ m/s^2 (see thin acceleration line in Fig. 1). This mode was supposed to last until the 227th second, but, in fact, 9 engines operated on it for only ~10 seconds, and then in 6 seconds, from the 191st to the 197th, they all turned off in a cascade. At the same time, at the 194th and 197th seconds, 2 powerful lateral flame emissions were noticed from the same area of the engine compartment, and all this ended with explosion and destruction of B9 stage at the beginning of 200th second of the flight [2].

Without going into all the details of this process, which was discussed in paper [2], we will only point out that the double excitation of Pogo at this phase of the booster's flight explains 7 of its specific features that were directly visible to the eye during this maneuver [2]. Moreover, in the episode under consideration, booster B9 own frequency of elastic oscillations f_e was estimated to be ~ 18.5 Hz [1], and taking into account multiplicity of 2, the approximate values of Pogo excitation bandwidth turned out to be as follows: $8.55 < f_n < 10.1$ (Hz).

Based on mass of the booster and value of its acceleration, the thrust of power plant and, accordingly, the operating modes of the engines in this phase of the trajectory were determined. It was found that during this maneuver degree of engines throttling was equal to ~ 0.70 [2]. From Table 2 (it contains the same notations as before) it is clear that with the length of the oxygen line from the pump to the gas generator $L_1 = 0.45$ m, with the length of the oxygen line from the tank to the pump $L_2 = 4.0$ m, as well as with the corresponding pressure drops across in the oxygen pump, it is quite possible double emergence of Pogo process [2].

Table 2

Rocket Stage Engine	**p_2/p_1**	**L_1 (m)**	**L_2 (m)**	**L_3 (m)**	**L_{eq} (m)**	**f_n (Hz)**
c = 930 m/s						
Starship Super Heavy Raptor-2	160	0.45	4.00	4.45	26.9	**8.64**
	155				26.5	**8.78**
	120				23.4	**9.94**
	110	0.45	4.00	4.45	22.5	10.3
	100				21.5	10.8

In this case, the visual manifestations of this maneuver will coincide with those phenomena that were noticeable in video [10]. In Table 2, the first two lines ($p_2/p_1 = 160$ and $p_2/p_1 = 155$) describe hydroacoustic frequencies during booster B9 turns on its windward and leeward sides, respectively, and the third line corresponds to its final flight phase without rotation ($p_2/p_1 = 120$), see [2]. The value of the parameter $L_1 = 0.45$ m is the same as for one of Pogo calculation options at the start. The fact that the values of L_2 in these calculation options differ isn't a contradiction, because the lengths of the oxygen lines from the tank to the pump for different groups of engines (3 central, 10 inner ring engines and 20 outer ring engines) must certainly be different. And Pogo, at least at the initial stage, can occur only on one of the groups of engines.

Now let's look at Fig. 1 to determine what changed during the first stage boostback on the third flight. It shows that its acceleration in the quasi-stationary braking section increased from 25 m/s^2 in the second flight to 30 m/s^2, which was provided by the operation of 13 engines compared to 9 in the first attempt at this maneuver. Therefore, now degree of throttling of the engines should have been about 0.58, and pressure drop across the oxygen pump should have diminished to approximately 100, see the last line in Table 2. In this case, the frequency of hydroacoustic oscillations increases from 9.9 Hz to 10.8 Hz and leaves "Pogo zone".

And during the previous turn maneuver in the third flight, all 13 engines also operated instead of the same 9 in its second half during second flight, so the engines thrust there was also reduced by ~ 9/13 times, which lowered the pressure drop at the pump from 160/ 155, to approximately 110. This increased the frequencies of hydroacoustic oscillations from 8.65/8.8 Hz to ~ 10.3 Hz, which also took them out of "Pogo zone", see Table 2. Thus, precise, strictly controlled reduction in engine thrust prevented the occurrence of Pogo and a stage explosion during boostback in the third flight of Starship.

VI. Analysis of Starship behavior during second and third flights in the vicinity of second flight's third critical point

The third critical point is the explosion of second stage (or Ship) at the end of its acceleration. The vehicle accelerated along the trajectory without any problems, its acceleration monotonically increased due to the decrease in mass because of fuel spending, until it reached a value of 35 m/s^2. At this point, to stop further increases in acceleration, the engines were put into continuous throttling mode so that the acceleration became constant. On the second flight, this happened approximately at the 461st second of flight (see Fig. 2). Immediately before this, the boost gases were released from the oxygen tank, which abruptly changed the frequency of hydroacoustic oscillations in the oxidizer supply line to the engines. In addition, a continuous decrease in thrust also monotonically increased this frequency, so that, quite expectedly, conditions arose for the emergence of another self-oscillatory process of Pogo type, and the engines began to turn off in a cascade, and at 483rd second an explosion of the second stage occurred (see [3]]).

The picture of everything that happened was qualitatively simple and clear, but its calculation was complicated not only by the fact that we didn't have and still don't have any accurate data on the design parameters of the fuel system of Starship second stage, but also by the fact that thrust of its power plant, consisting of three conventional Raptor-2 engines and three of the same engines with a so-called "vacuum nozzle" was reduced long before the 460th second of flight. Estimates of the stage mass and its acceleration showed that the degree of throttling of the power plant as a whole at the break point of acceleration curve should have been close to 0.83. It seems most reasonable was throttling the conventional Raptor-2 engines, which are less efficient under these conditions, to 0.64, while "vacuum" engines with nozzles of significantly larger expansion would operate at full rated thrust (see [3]).

Made analysis of the two previous critical points of Starship second flight was made it led us to the conclusion that the most probable value of the acoustic length (see [5]) of the oxygen line from the pump to the gas generator in Raptor-2 engine $L_1 \approx 0.45$ m. Consequently, we recalculate those given in the paper [3] frequencies of hydroacoustic oscillations with slightly modified input data, see Table 3. Of course, these are model calculations, and the real characteristics of both engines and their fuel systems may differ somewhat from those accepted here, but these estimates illustrate a simple and quite obvious mechanism for the occurrence of Pogo when the degree of engine throttling changes.

Table 3

Rocket Stage Engine	**p_2/p_1**	**L_1 (m)**	**L_2 (m)**	**L_3 (m)**	**L_{eq} (m)**	**f_n (Hz)**
c = 930 m/s						
Starship Ship Raptor-2	*170*	0.45	2.70	3.15	22.7	10.2
	140				20.6	11.3
	110				18.3	**12.7**
	125				19.5	11.9
	170	0.45	3.00	3.45	24.0	9.70
	140				21.8	10.7
	110				19.3	12.0
	125				20.6	11.3

It is assumed that after the release of excess boost gases at that time, a nominal pressure p_1 = 0.40 MPa was established at the inlet to the oxygen pumps of the engines. Then, at nominal thrust, the pressure drop across the pump is $p_2/p_1 \approx 170$. And with the length of oxygen line from tank to pump L_2 = 2.70 m, which we consider to be the value corresponding to the actual length for three central conventional Raptor-2 engines of the second stage, we would get frequency of hydroacoustic oscillations f_n = 10.2 Hz (see the first group of results in Table 3). However, as we assumed, these engines were throttled with reduction in thrust to 0.64 of the nominal, and in this case $p_2/p_1 \approx 110$, and f_n = 12.7 Hz, which is already inside Pogo excitation zone, since the own frequency of elastic oscillations the second stage hull in this phase of trajectory is estimated to be f_e = 23.5 – 27.5 Hz (see [3]). Then, with a multiplicity of 2 and maximum possible frequency difference of ± 8.5 % (see [5]), Pogo excitation zone is located at a hydroacoustic frequency of $12.1 < f_n < 14.4$ (Hz), and with a multiplicity of 3 – at $8.1 < f_n < 9.6$ (Hz).

At the same time, the vacuum engines operated at nominal thrust ($p_2/p_1 = 170$), and at frequency $f_n = 9.7$ Hz in their oxidizer lines Pogo process wasn't excited. The value $p_2/p_1 = 140$ corresponds to the same throttling of both engine options. It turns out that if this were so, then the second stage would not have exploded shortly after passing the described point. Possible but unrealized options in Table 3 are indicated in column p_2/p_1 in oblique font.

The last, fourth lines in each group of lines presented in Table 3 already refer to Starship third flight. Due to the fact that the second stage acceleration was completed successfully, and also because the two groups of second stage engines weren't turned off simultaneously, it became possible to determine how the second stage engines were throttled in the third flight. And this time their throttling was the same for all engines. The fact that after turning off the vacuum engines the thrust of power plant decreased by more than 2 times is explained by the fact that their thrust at low ambient pressures is approximately 5 % higher than that of conventional Raptor-2 engines. Then it would be necessary to consider the unrealized earlier option with a drop $p_2/p_1 = 140$, however, in the third flight, the release of excess boost gas wasn't carried out on the acceleration trajectory. Instead, this procedure appears to have been performed during passive flight and appears to have introduced strong disturbances to the second stage's motion relative to its center of mass, which may have ultimately led to its reentry into the atmosphere at incorrect position and to death because of improper braking mode. Additionally, Ship was unable to fire one of its engines in zero gravity, which moves this round of SpaceX game with Pogo in Russian roulette to the next flight.

However, in the third flight, the pressure in front of oxygen pump in final phase of second stage acceleration trajectory wasn't brought to nominal value, and therefore, we estimated the magnitude of the oxygen pressure drop across the pump when the tank has been overinflated $p_2/p_1 \approx 125$, which was also quite safe for the vehicle at the point of transition to the mode constant acceleration. However, a further decrease in the mass of the stage leads to an increase in the frequency of its own elastic vibrations. And by the end of the acceleration the second stage can again fall into the "pogo zone", but already at a multiplicity of 3 for hydroacoustic oscillations. That is, it is no longer the upper limit of the operating range that becomes dangerous, but the lower one.

And in "pogo zone" first turn out to be engines with longer oxygen supply lines, that is, obviously, vacuum engines located further from the stage central axis (see Table 3, remembering that the actual length L_2 may well be larger than 3.0 m). Therefore, to prevent the appearance of a new Pogo variant, they have to be turned off them even before the acceleration of the second stage is completed. This explains the strange at first glance completion of the second stage acceleration with the earlier shutdown of more efficient engines. And, if the oxygen tank hadn't been overinflated in the third flight, then this moment would have come earlier, and, perhaps, the acceleration of the second stage would not have been completed at all. To accurately answer this question, accurate technical information about the second stage is required.

VII. Analysis of Starship behavior during third flight in the vicinity of this flight's first critical point

The second and third critical points of the third flight (not starting the engine in zero gravity, which, if started, could have terminated the existence of the second stage somewhat earlier than it actually happened, as well as its uncontrolled entry into the dense layers of the atmosphere) were briefly described in the previous section.

Let's now consider in more detail the first critical point of Starship third flight, relating to splashdown of the first stage on the ocean surface. Let's go back to looking Fig. 1. After the first stage has been turned by boostback to fly in the opposite direction, and has been moved for approximately 100 seconds almost exclusively by gravity between the 270th and 370th seconds, the influence of the atmosphere began to be noticeably felt at altitude of about 45 km and at speed 1.10 km/s. Aerodynamic drag slowed down first the growth of the stage speed (the maximum value $v \approx 1.20$ km/s was reached at the 385th second of flight at an altitude of 25 km), and then its speed began to decrease. Maximum braking was achieved at 400th second at a speed of about 0.8 km/s and an altitude of 9 km. The acceleration at this moment was 48 m/s^2.

According to iconography of video stream [4], first engine, one of the three central ones, turned on at the 414th second of the flight. During the same second, 2 more inner ring engines joined it, and jet braking began at an altitude just below 1.0 km at the speed of about 365 m/s. A second later, one of engines switched off, and after another 4 seconds, the first stage, Super Heavy, exploded at altitude of about 0.5 km above sea level and at a speed of 310 m/s. So, 3 engines instead of the planned 13 were able to slow down the booster in 5 seconds at 50 – 60 m/s. According to Fig. 1 we can show that any noticeable engine braking continued from the 416th second to the 419th, until the explosion. Note that before splashdown the stage detonation system was deactivated.

So, according to plan, the booster should have started decelerating from an initial speed of $v = 0.36 – 0.37$ km/s at approximately an altitude of $h = 1.0$ km. Since the flight path here is close to vertical, in our estimates we will not distinguish between its length and height. With constant acceleration w, the change in speed v from 370 m/s to 0 at a distance of 1000 m according to the formula

$$w = \frac{v^2}{2h}$$

is required an acceleration value of $w \approx 70$ m/s^2. Taking into account the acceleration of gravity, the total acceleration will be about 80 m/s^2.

It is believed that the dry mass of the booster is 200 tons. With a specific impulse of the engines of 3.2 km/s [12], it could be slowed down from a speed of 0.37 km/s with a consumption of 25 tons of fuel. Taking into account gravitational losses, fuel consumption for final maneuvers and reserves, we will assume that in this operation an object with launch mass of 240 tons, and with an average mass of 230 tons should been slowed. Then, with an acceleration of 80 m/s^2, thrust of 18.4 MN is required. The nominal thrust of 13 Raptor-2 engines at sea level is 29.4 MN. That is, degree of throttling of these engines in this mode should be about 0.63. Taking into account the fact that the thrust drops somewhat faster than the pressure decreases in the main combustion chamber of the engine, we will take the pressure ratio on the oxygen pump equal to the value $p_2/p_1 \approx 110$.

It is important that in this mode, oxygen entered the engines not from the main tank, but from a small landing tank located inside the main tank, see Fig. 3. Diameter of the liquid oxygen landing tank is 3 m. It is raised by approximately the same amount above the bottom of the main oxygen tank (see [13]). Therefore, the length of the liquid oxygen lines from the landing tank to the pump of Raptor-2 engines should be about 5.5 – 6 m. With a length of $L_1 = 0.45$ m and $L_2 \approx 5.5$ m, the frequency of hydroacoustic oscillations is $f_n \approx 9$ Hz.

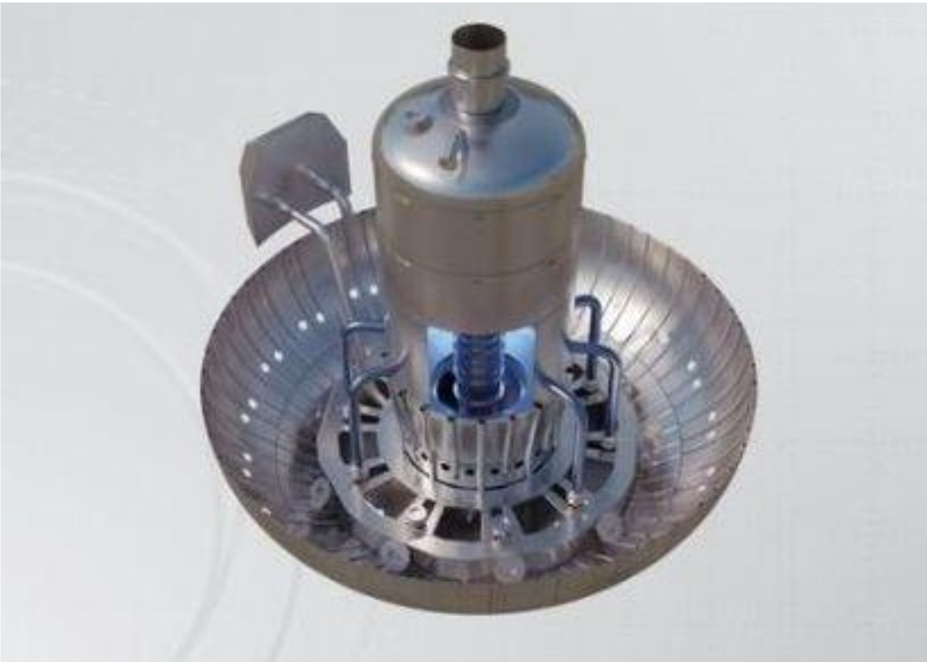


Fig. 3 – Image of liquid oxygen landing tank [13]

Estimates of the frequency of the booster hull own vibrations before landing using the method outlined above give the value $f_e \approx 26.2$ Hz. So it is possible to excite Pogo when landing at a multiplicity of 3 and a frequency quite close to the value $f_n = 8.7$ Hz. Since the process developed faster than ever, we can conclude that the frequencies of the two processes involved in Pogo were very close. And indeed, just as expected from the data in Fig. 3 length of the engines lines produces exactly these frequencies of hydroacoustic oscillations, see Table 4.

Table 4

Rocket Stage Engine	p_2/p_1	L_1 (m)	L_2 (m)	L_3 (m)	L_{eq} (m)	f_n (Hz)
c = 930 m/s						
Starship Super Heavy Raptor-2	110	0.45	5.30	5.75	25.9	**8.98**
			5.65	6.10	26.8	**8.68**
			6.00	6.45	27.6	**8.42**

Thus, without a doubt, the inexplicable, judging by some comments, explosion of the booster at final phase of its return from Starship third flight was caused by the same reasons as all the previous explosions of the stages of this rocket system – another excitation of Pogo process. After everything that has been written in this work, recommendations for eliminating this accident are completely trivial.

VIII. Paradox of Starship two test flights: Way of resolution

So, in the previous sections of this work it was shown how all three processes of Pogo type discovered during the second flight were eliminated in the third flight in all three cases in the same way – by changing the operating modes of engines, which led to a change in the frequency of hydroacoustic oscillations in the feeding lines with oxygen, and to rupture of positive feedback between them and the elastic vibrations of the hull. Fortunately, the throttling range of Raptor-2 engine is record-breaking. However, for this it was necessary to know how the thrust of the engine and the frequency of flow oscillations of liquid oxygen are related to each other. The author, having a theory of the process and a calculation method, could easily calculate dozens and hundreds of options for excitation and extinguishment of Pogo, but how were SpaceX employees able to do this a month and a half before mid-March 2014 without theory?

The assertion that they suddenly created this theory in the shortest possible time is completely refuted by a simple fact – if they did this, then why didn't they calculate the process of excitation of Pogo when landing the booster, which, given the parameters of the vehicle and the operating mode of the power plant known to them in advance, is computed very easily? This is perhaps the simplest of all 5 cases of Pogo excitation identified so far. Moreover, in the three previous cases, changes in the control of engine operating modes were made exactly as necessary to prevent Pogo – no more, no less. The naked eye can see that they were not acting blindly. But how?

The answer to this question turns out to be very simple – they were able to calculate the necessary changes in engine operating modes for those cases that had already occurred, that is, when they had experimental data on the frequencies of both hydroacoustic and elastic vibrations. It follows from the theory that "in the hydroacoustic systems under consideration with large or very large pressure rises, with a constant geometry, their frequency is inversely proportional to the square root of the pressure rise in pump with a high degree of accuracy" [5]. And this was being repeated 4 more times in papers [1, 11, 14, 15]. That is

$$f_n \sim \sqrt{\frac{p_1}{p_2}} \qquad (1)$$

Thus, if from the results of the previous accident investigation the frequencies and operating modes of the engines are known, then with a constant length of the fuel pipelines using formula (1) it is easy to determine the desired operating mode of the engines, which will allow avoiding an accident on the next flight.

But the accident during landing of the booster hadn't yet occurred before the start of the third flight. And oxygen in this mode was supplied from the landing tank through pipelines of other length. Therefore, recalculation in this case is impossible, you just need to solve the corresponding system of equations, and SpaceX Company doesn't know how to do this. The system of equations itself is also unknown. Therefore, SpaceX can use the method of recalculating the results only from one accident to another. And when she switches to a new version of the Starship V2 or V3, for it this whole path from accident to accident will begin all over again.

IX. Paradox of Starship two test flights: Possibility of going this way

The previous section described a way in which SpaceX could quickly change the operating modes of the propulsion system of both Starship stages in order to prevent, on its third flight, 3 cases of excitation of self-oscillating Pogo process that arose in the second flight. With such a "catastrophic" way of solving problems, knowledge of formula (1) is critically important. Let us now consider the question of whether SpaceX employees could have become acquainted with it in the period between the second and third flights of their rocket system, and if so, how and when this happened.

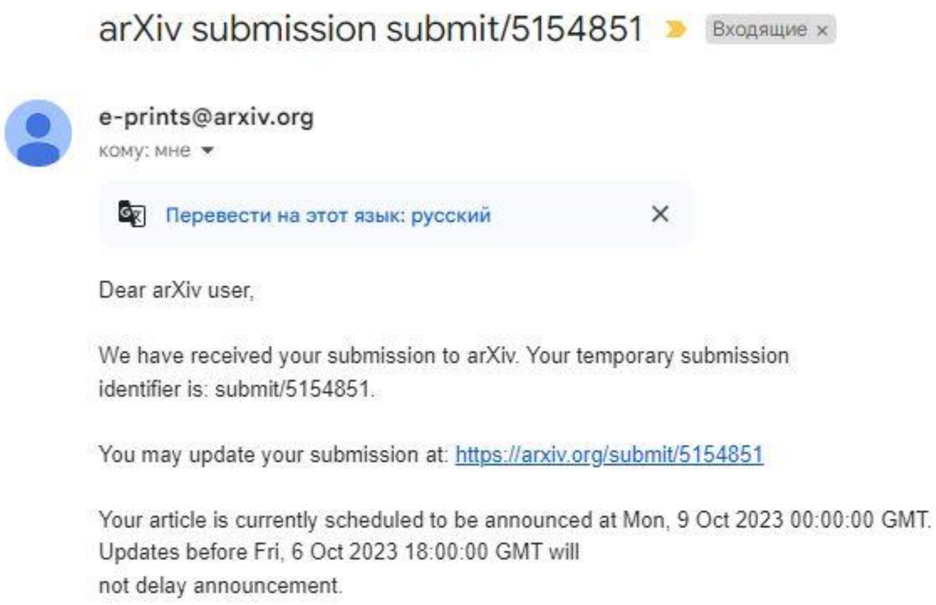


Fig. 4 – Message of arXiv about announcement of paper "Cause of Starship crash on first flight" on October 9, 2023

On October 5, 2023, the author of this work sent to arXiv.org paper [5] with analysis of Starship first flight results, where, among a large volume of information, for the first time in the public domain, the relationship was described between the frequency of hydroacoustic oscillations in the rocket engine feeding line and the pressure drop across its pump, expressed by the formula (1). This document was planned to be published on October 9, see fig. 4.

However, this paper wasn't made available to arXiv readers either on October 9 or later. The day before, it was unexpectedly transferred to "on hold" status, see Fig. 5, and in this state it remained until November 6, 2023 – 32 days from the date of filing. Apparently, arXiv experienced a record delay in publishing a paper due to unannounced and unclear reasons.

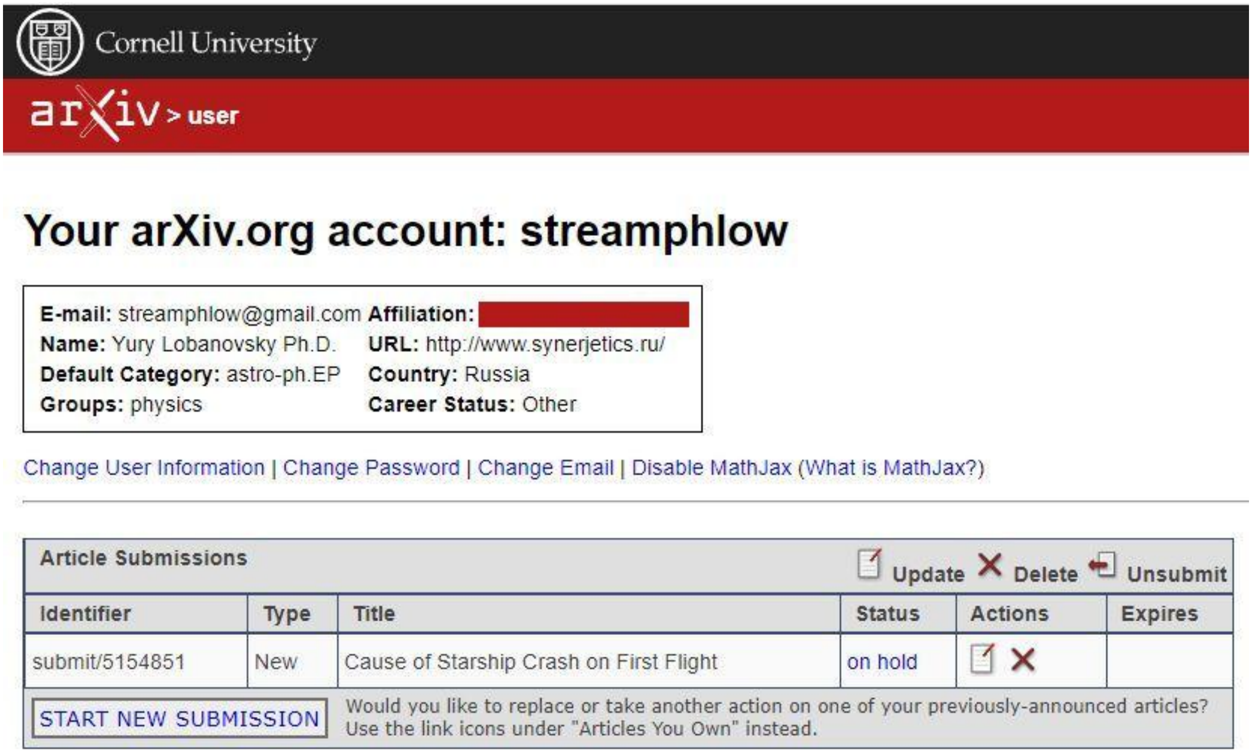
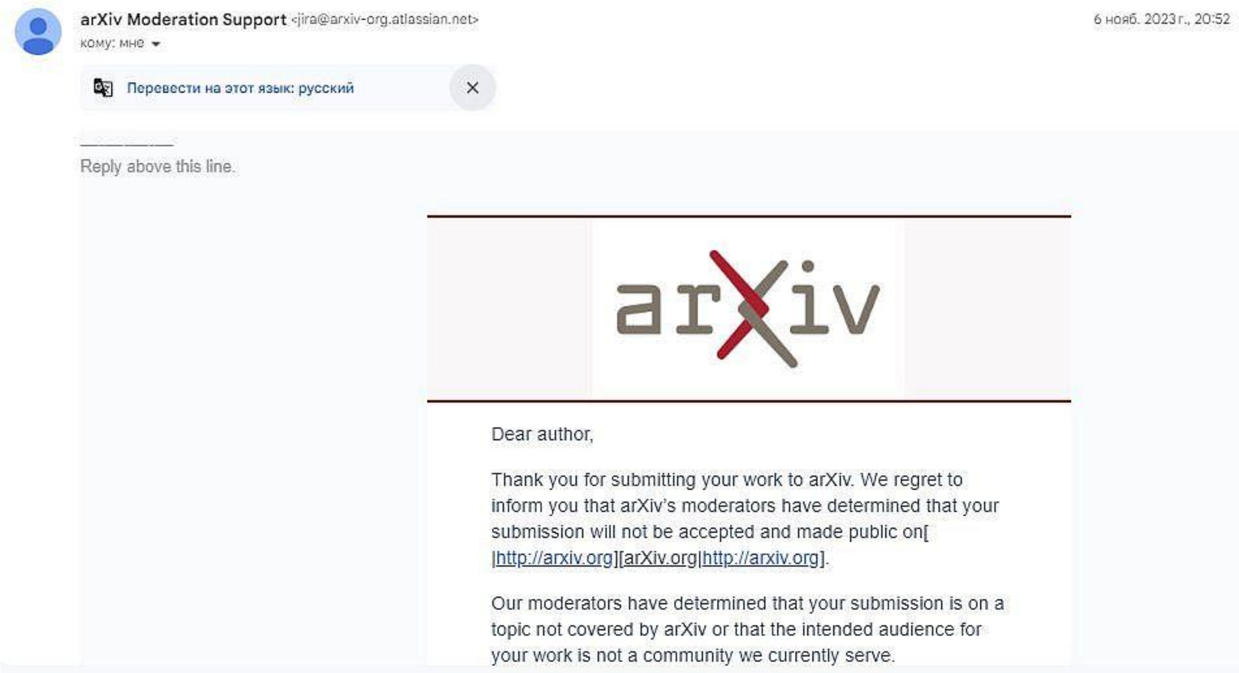


Fig. 5 – Window of paper current status in arXiv

The author's repeated attempts to find out for what reason and until what time this regime will continue were met with responses that were amazingly polite and vacuous: "We apologize for the delay with your submission.

Unfortunately, we do not yet have a final decision from the moderators, but we have reminded them that a decision is still pending for your work.... Please know that we are a small, US-based team, working business hours Monday–Friday..... Once a decision has been made, your article will either be deposited in arXiv, or we will contact you with further information. Please continue to be patient". And later, at the end of October: "Due to the current climate we have been experiencing longer than expected delays for some moderation decisions. Your submission will remain in "on hold" status until a decision is reached. Unfortunately we cannot provide a time-frame for a resolution to this state. We apologize for the inconvenience".

Finally, on November 6, 2023, after more than a month of activity for purposes they were unable or unwilling to explain to the author, the decision was made: "Our moderators have determined that your submission is on a topic not covered by arXiv or that the intended audience for your work is not a community we currently serve", see Fig. 6. At the same time, they didn't fulfill their promise, never contacting the author "for additional information", and also didn’t report what kind of "current climate" they was there.


arXiv Moderation Support <jira@arxiv-org.atlassian.net>

6 нояб. 2023 г., 20:52

кому: мне

Перевести на этот язык: русский

Reply above this line.

arXiv

Dear author,

Thank you for submitting your work to arXiv. We regret to inform you that arXiv's moderators have determined that your submission will not be accepted and made public on[|http://arxiv.org][arXiv.org|http://arxiv.org].

Our moderators have determined that your submission is on a topic not covered by arXiv or that the intended audience for your work is not a community we currently serve.

Fig. 6 – Decision of arXiv moderators on the paper about Starship first flight

And the reason for the refusal was again not formulated. What was it, either the topic (the theory of self-oscillations!) cannot be considered in arXiv, or it is of no interest to anyone (despite the fact that 4 months after this verdict, this work that soon became available to SpaceX made it possible to carry out the third flight of Starship, the results of which have significantly exceeded all what was previously)? Thus, the normal process of publication of the paper was unexpectedly stopped, and at the same time access to the information contained in it was given to an unknown number of people.

A month later, after Starship second flight, on December 6, 2023, on the famous aerospace forum NSF (NASASpaceflight) in topic "Re: SpaceX Starship IFT-2: Starbase TX: 18 Nov 2023 DISCUSSION" author posted a short information about the paper, which was rejected by the anonymous moderators of arXiv, and wrote 9 lines about the topic of that work (see [16] and Fig. 7). This short post caused such a heated discussion on NSF forum that it soon suppressed all other issues discussed there in thread about the second flight of Starship. In this regard, one of experienced forum members – Robotbeat from Minnesota created a separate new topic "Streamflow's pogo oscillation theory regarding Starship (esp IFT-2)" on December 15 to continue discussing this issue (see [17] and Fig. 7).

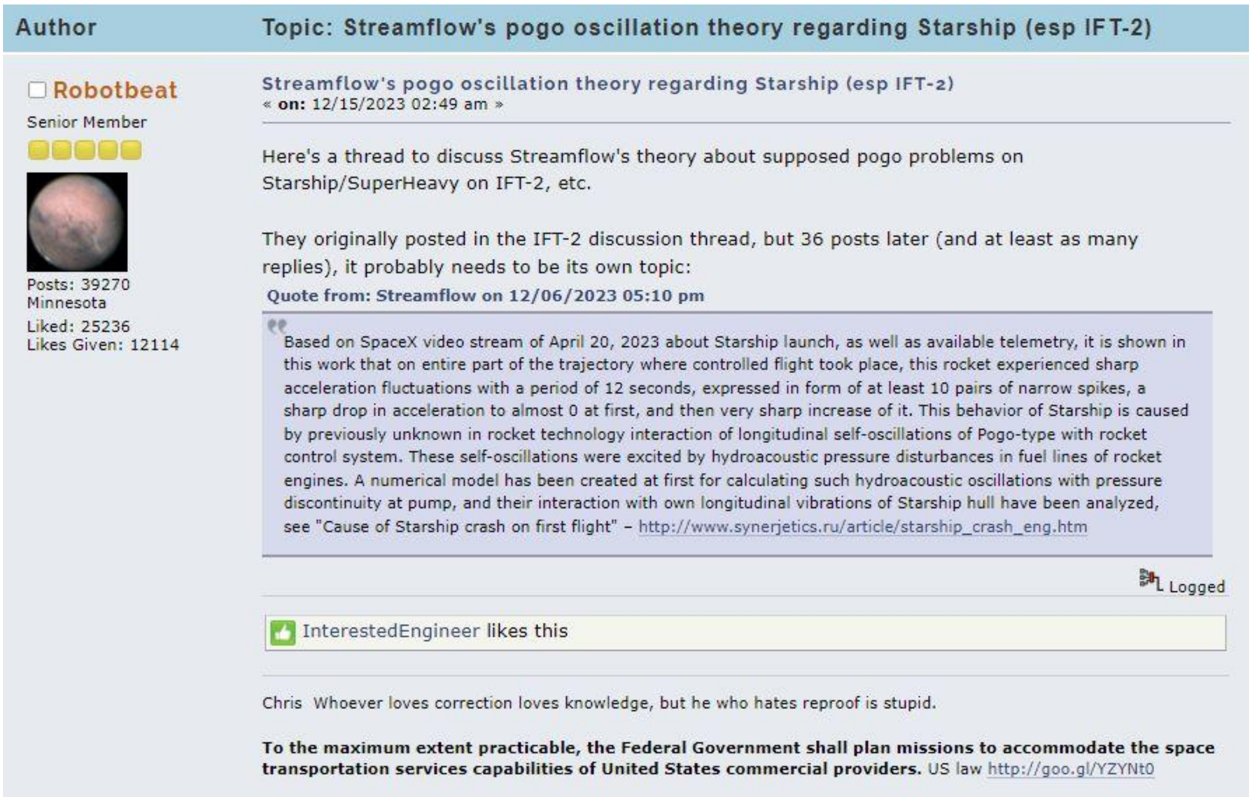


Fig. 7 – Opening of topic "Streamflow's pogo oscillation theory regarding Starship (esp IFT-2)" on NSF forum

Discussion continued in a new topic, during the day 23 posts appeared in it, and 1918 views were made, but right while the author was writing the 24th post – an answer to a question from one of the forum participants, the topic was blocked without any explanation by an unnamed site administrator. This happened only 13.5 hours after its opening (see Fig. 8).

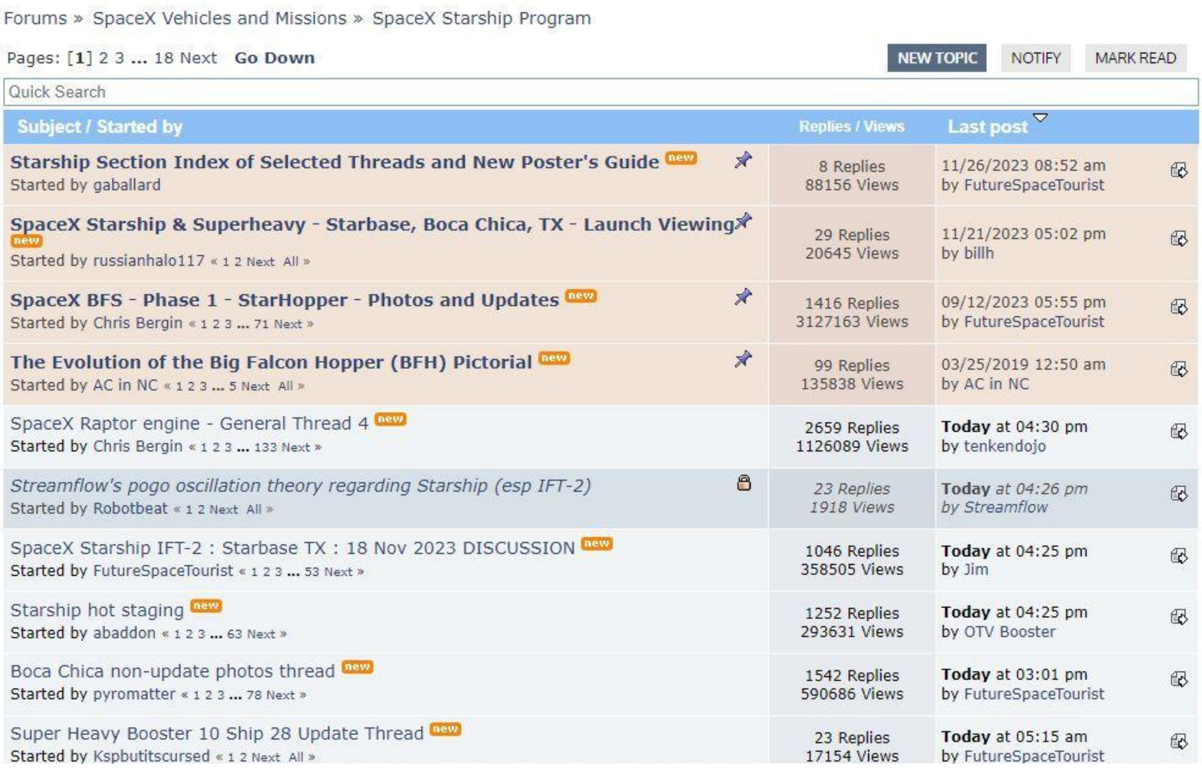


Fig. 8 – List of topics on NSF forum a few minutes after "Streamflow's pogo oscillation theory..." topic closing

In the topic there was an active and quite friendly discussion about Pogo type self-oscillations without any attacks on Starship or SpaceX, there wasn't even a hint of a violation of any forum rules, however, this blocking occurred, and after that access of user Streamflow to the forum of was also closed. But, even closed and buried deep in the list of forum topics, this topic was regularly visited by forum participants, and as of March 30, 2024, its counter indicated 5202 views. Moreover, it later turned out that Streamflow was then denied access to an indefinite number of administrative and information sites throughout all Cameron County, Texas, where the notorious settlement of Boca Chica is located. At the same time, access was prohibited of all Internet users with a Russian IP address.

It is interesting to note that, according to available information, no later than December 14, 2023, SpaceX President and Chief Operating Officer Gwynne Shotwell became aware of the work [5]. And, apparently, the reaction from her or her nearest circle was immediate. Otherwise, it is difficult to find any figure so interested in this issue and capable of simultaneously taking measures to block access to the famous site registered in England, and, at the same time, blocking access to an entire county from state of Texas. At the same time, from that moment on, an almost complete cessation of any messages from SpaceX and its entourage related to Starship past flight, as well as about immediate plans for the future was noticed. The last one was a speech on December 12, 2023 by Kathy Lueders, head of Starbase, rocket site from which Starship is launched, in Brownsville, by the way, main city of Cameron County [18]. That is, it was decided to apply the principle: "No one knows about the problem, which means it doesn't exist".

This silence was broken only on January 12, 2024 by E. Musk's speech at the test site in front of its employees [8], which, as mentioned earlier, fairly approximately reflected the real course of events during the second flight [3]. However, according to available information, no later than January 21, SpaceX Vice President, Build and Flight Reliability William Gerstenmaier became aware of 6 articles by author of this work, which analyze Pogo-type processes in Starship, and principle of non-recognition of the problem was discarded soon. Judging by reports from representatives of circles close to SpaceX, sentiments regarding the timing of Starship third flight have also changed. As early as February 1, it was reported: "The FAA is on pace to issue a Starship launch license mid to late February, I'm told, in what is shaping up to be a busy month" [19], and already on February 7 they began to write something opposite: "The return to flight of the SpaceX Starship Super Heavy vehicle requires the OFT-2 launch mishap investigation to be closed and the license modification for the OFT-3 launch to be approved. The SpaceX-led mishap investigation remains open and SpaceX has not yet submitted all needed information for the license modification" [20]. Knowing how much the FAA follows in the fairway of SpaceX, it is difficult to doubt that these statements primarily reflected the position of the company itself.

A systemic analysis of all the information presented in this section of the work leads to an almost unambiguous conclusion: in the period from February 1 to February 7, 2024, SpaceX attitude to Pogo problem, as well as to the theory that describes it and was presented at that time in six articles [1 – 3, 5, 11, 14] changed, and 5 – 6 weeks before March 14, the engine control algorithms at three critical points of Starship second flight were changed. This has led to clear progress in identifying and eliminating problems facing the developers of this system. But the impossibility of fully using this Pogo theory didn't allow the booster to complete its flight as planned. And after a simple corollary from the theory has shown what its use leads to, it would be natural to begin to apply the theory in full, and not in a reduced form.

Conclusions

1. In the third flight of Starship, SpaceX demonstrated that all 3 Pogo cases identified in the second flight, 2 of which led to explosions of both stages of the system, were successfully eliminated just 4 months after the second flight by precise and strictly controlled changes in the operation of Starship engines.

2. At the same time, no attempts were made to prevent Pogo process that reappeared and also ended in an explosion in a previously untested flight mode – splashdown the booster on a ocean surface.

3. This means that when changing the power plant control algorithms, previously obtained experimental "pre-emergency" data and recalculation of hydroacoustic oscillations frequencies by engine operating modes were used, following from Pogo theory created by author of this work in the spring – summer of 2023, and which became limitedly available to SpaceX no later than mid-December 2023.

4. In the period from the beginning of October 2023 to the end of January 2024, no less than five public and business structures attempted to block information about this theory. However, after some time, policy of SpaceX changed radically, and in February – early March 2024, it applied the consequences available to it from Pogo theory to change the operating algorithms of Starship power plant, thus ensuring that it successfully passed on the third flight that modes which ended in explosions on the second.

5. Thus, without the full use of Pogo theory, SpaceX will be forced to sequentially go from one accident to another, experimentally identifying all possible Pogo cases for which Starship is a natural habitat. This will continue to happen as new versions of this rocket system are transitioned, making their development a never-ending sequence of accidents and potentially exhausting the resources available to the company to continue this exciting process.

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30.03.2024

Yu. I. Lobanovsky