Explosion mechanism of Starship second stage during second flight at the end of its acceleration

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You die today, and I die tomorrow.
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Summary

This work shows that explosion of Starship second stage during second test flight occurred at the final stage of acceleration due to the emergence and development of Pogo-type self-oscillations with hydroacoustic disturbances in the oxygen supply line for the engines. Conditions in which self-oscillations arose occurred during boosting gas was vented from oxygen tank of the second stage, due to a sharp change in pressure at the inlet of oxygen pumps of rocket engines, when they are also throttled.

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

Symbol list

c – speed of sound
f_e – own frequency of rocket hull
f_n – frequency of hydroacoustic oscillations
g – acceleration of free fall
h – height
L – length
L_{eq} – equivalent length of oscillatory circuit
m – mass
p – pressure
v – speed
w – acceleration
Δ – difference symbol
< > – averaging symbols

I. Introduction

The reason for the explosion of Starship second stage (Ship) in the second test flight (IFT-2) at the finish of its trajectory acceleration section absolutely was not clear to SpaceX, the developer of this rocket system, for quite a long time. According to a statement by Kathy Lueders, head of Starbase, test site from which it was made, on December 12, 2023, that is, 3.5 weeks after IFT-2, that "Starship's anomaly investigation team was still looking into why the Nov. 18 flight's Automated Flight Termination Systems were activated" [1]. Then a month of silence followed, and finally, on January 12, 2024, Elon Musk, in his speech at the test site in front of his employees, said that "...the reason that it [Ship] actually didn't quite make it to orbit was we vented the liquid oxygen, and the liquid oxygen ultimately led to fire and an explosion. Because we wanted to vent the liquid oxygen because we normally wouldn't have that liquid oxygen if we had a payload". And further: "And so I think we've got a really good shot of reaching orbit with flight three and then a rapid cadence to achieve full and rapid reusability".

In work [3], written 2 weeks after the second flight, however, the following was stated: "It was demonstrated... that the cause of the second stage failure in the second flight at the end of the operating mode was caused by the occurrence of Pogo when throttling its engines". But due to the fact that there was no data on the quantitative parameters of the stage and its power plant at that time, this statement was therefore justified by qualitative reasoning. Now, a month and a half later, using the experience gained when considering the causes of Starship first stage explosion on the second flight [4], and also, based on information from the speech of E. Musk [2], within the framework of self-oscillations of Pogo concept, we will carry out a more thorough investigation of the second stage incident using quantitative data.

II. A picture of what happened and assessments of the second stage quantitative characteristics and parameters of its power plant in the final stage of its acceleration

Let us first investigate flight dynamics of Starship second stage on its second flight. To do this, consider the graph from the source [5] previously presented in [3], see Fig. 1.

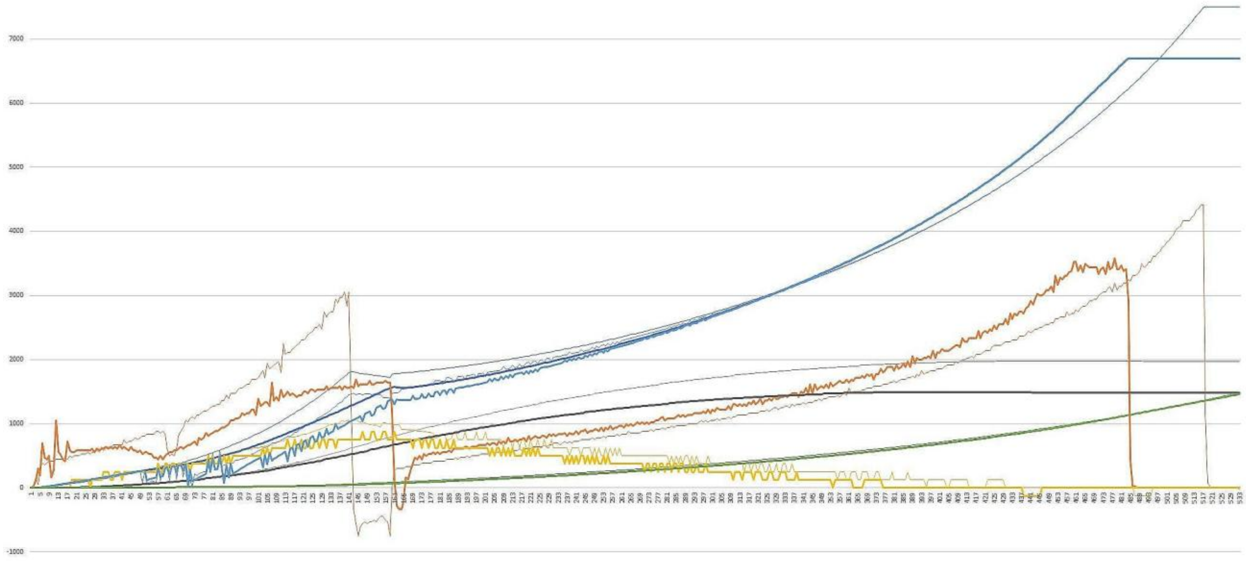

Fig. 1 – Acceleration, speed, altitude, direct range, as well as horizontal and vertical velocities of Starship in the second flight in comparison with similar parameters of Falcon-9 rocket [5]

It's shown in Fig. 1 (see [5]) a comparison was made over time (in seconds) of six Starship parameters with similar characteristics of Falcon-9 rocket, namely: acceleration (in cm/s^2), speed (in m/s), trajectory altitude (in hm), direct (horizontal) flight range (in km), as well as horizontal and vertical speeds (in m/s). Data related to Starship is displayed in thick lines, and data related to Falcon-9 is shown in thin lines. Acceleration is shown with purple curves, speed with blue curves, altitude and range with black lines...

But now, strictly speaking, we are only interested in the acceleration of the second stage at the final phase of acceleration, where this rapidly growing upward line (due to a decrease in the mass of the stage) transforms, up to some oscillations, into a horizontal straight line, and the acceleration value is fixed at the level $w \approx 35$ m/s^2. In the concept of self-oscillations, this is precisely what caused the explosion of the second stage. Note that this isn't the case with the second stage of Falcon-9 – there the acceleration increases until its only engine is cut off at an acceleration level of $w \approx 44$ m/s^2.

Apparently, this difference is mainly due to the fact that Starship is a really large rocket, in which the pressure in the fuel tanks is strongly influenced by hydrostatic pressure of fuel components, especially increasing as the longitudinal acceleration of the rocket increases. For example, already at an acceleration of 35 m/s^2, each meter of the thickness of the oxygen layer adds about 40 kPa to the pressure at the bottom of the oxygen tank, while the nominal pressure at the inlet to both pumps of Raptor-2 engine used by Starship is 400 kPa, and maximum the permissible pressure in the main tanks of the system is 600 kPa (see, for example, [4]). So, taking into account the length of vertical (longitudinal) sections of the fuel pipelines to the engines, at high accelerations, even in almost empty tanks, the hydrostatic pressure can be so high that these accelerations would need to be limited in flight. Judging by the available data, the maximum permissible acceleration of both elements of Starship shouldn't exceed $w \approx 35$ m/s^2. In addition, this may require reducing the boost pressure in the fuel tanks by releasing boost gases into the surrounding space, which, for example, should be done in Starship first stage (booster) before staging and sharp increases in booster acceleration during the return maneuver [4].

So, judging by the available data, the maximum permissible acceleration of both elements of Starship shouldn't exceed the value $w = 35$ m/s^2, and when it approaches this value, it is necessary to discharge boosting gas of the fuel tanks.

Let us analyze the data we have, albeit approximate and incomplete, to find out what happened in the oxygen tank of the second stage during the final phase of its acceleration trajectory. To do this, let's carefully look at enlarged fragments of some video frames [6], see Fig. 2, at the times indicated in the signature.

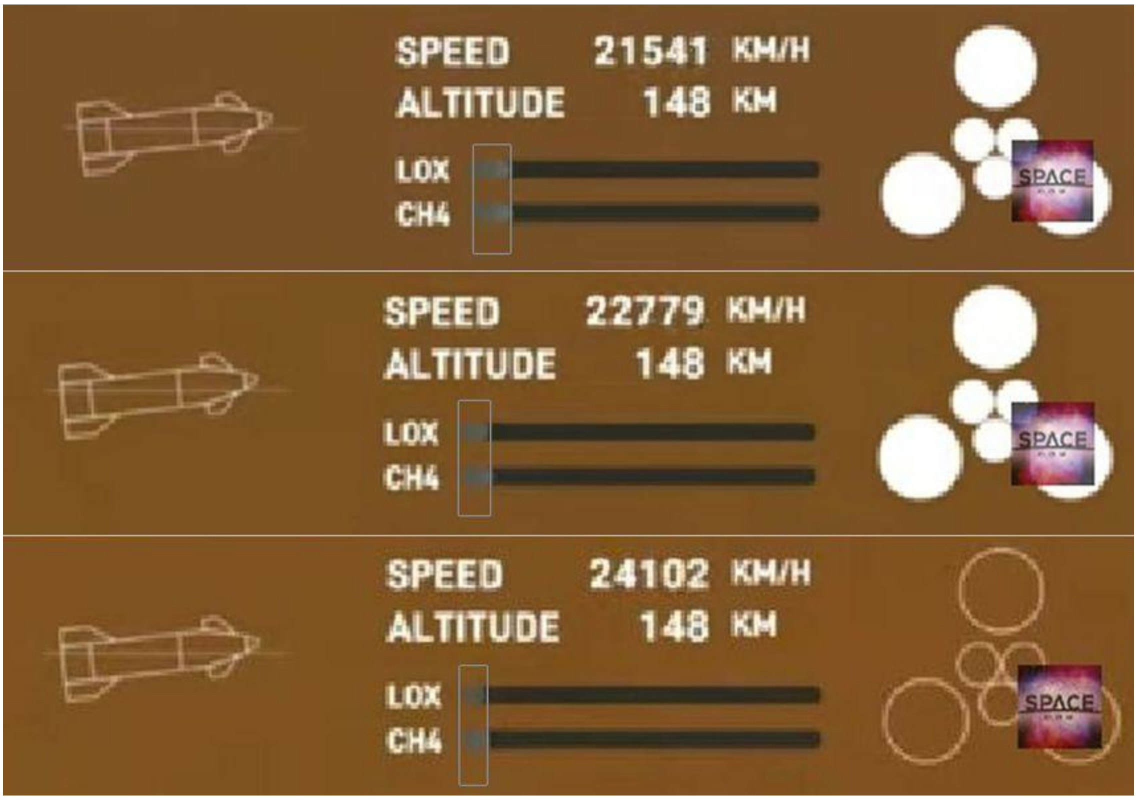

Fig. 2 – Amount of fuel components in the second stage tanks at times 463, 473 and 483 (s) (from top to bottom)

In this case, the beginning of fixing the acceleration of the second stage at a given value (the break point of the acceleration graph in Fig. 1), that is, the beginning of the corresponding (additional) throttling of the stage engines happened approximately on 461st second of the flight, and at the 483rd second of the flight the engines turned off (see Fig. 2) and then there was an explosion. Taking into account the accuracy that can be expected from these images, we can assume that by 463th second of flight no differences were detected between the proportions of fuel components remaining in the tanks, 10 seconds after that there are still some very small differences, and also after 20 seconds, just before the explosion, the proportion of oxygen in the tank was 5 % less than methane. That is, liquid oxygen, as E. Musk said [2], in the last 15 – 20 seconds of the flight was consumed somewhat faster than methane (in relative proportions). But there was no immediate release in fact.

But at the same time, a careful study of video frames [6] showed that there was a simultaneous release of substance from the second stage at 460th second, immediately just before the start of the program reduction of engine thrust to stop of the second stage acceleration increase, see Fig. 3 – 6.

Fig. 3 – Static picture of a rocket flight at high altitude

At the 459th second, the second stage performed a regular flight, during which the condensed components of the expanding jets of engines exhaust gases, illuminated by the Sun, created an almost static image (Fig. 3).

Fig. 4 – The beginning of "plume" expansion due to release of matter into the surrounding space

After a few tenths of a second, a denser than a jet stream "plume" appeared from the substance thrown overboard (Fig. 4).

Fig. 5 – Expansion of "plume" and its departure from the stage

In less than 1 second, it moved away from the stage and after that continued its rapid and irreversible expansion in space (Fig. 5).

After just 1.5 – 2 seconds, "plume" dissipated almost without a trace in space (Fig. 6). However, this phenomenon could not have any noticeable effect on the amount of liquid oxygen in the tank (see the top image in Fig. 2, where the situation was recorded 1 second after the one shown in Fig. 6), and the explosion occurred only after more 21 seconds at T +00:08:03 [3].

Fig. 6 – Restoring static picture of a rocket flight at high altitude

From the totality of data, it is quite obvious that at the 460th second of flight, boosting gases were released from the oxygen tank, consisting of oxygen, diluted with a relatively small amount of methane combustion products with a large excess of oxygen – mainly carbon dioxide and water vapor. At the same time, the fuel pressure at the inlet to Raptor-2 oxygen pump dropped so much that it apparently became nominal.

Let's estimate mass of the stage at 461st second of flight, own frequency of its elastic oscillations, as well as thrust of its engines. We need to determine the operating mode of the stage engines at this time. The total nominal thrust of three conventional and three high-altitude Raptor-2 engines in vacuum is 15.5 MN [7]. With acceleration w = 35 m/s^2, then the mass of the stage should be at least 440 tons.

Now let's estimate it differently: the initial flight speed of the stage is 1.55 km/s [5, 6], and at the point of interest to us it is equal to 5.92 km/s, and increment in flight speed Δv = 4.37 km/s. Then, with an average specific impulse of conventional and high-altitude engines Raptor-2 (with a predominance of high-altitude thrust, see below), equal to 3.66 km/s [7] according to Tsiolkovsky formula with a starting mass of the stage of 1300 tons [8], the mass of the stage at this point was would be equal to 395 tons.

However, losses must be added to the change in velocity as such. The average value of gravitational losses and control losses, that is, total losses for the second stages of three rockets, which include Saturn V, Zenit-2SLB and Titan II, was 510 m/s [9]. Of course, the acceleration trajectory of such a reusable object as Starship differs significantly from the trajectories of expandable launch vehicles due to joint optimization of its both acceleration and returns sections. It is significantly steeper, and, therefore, a significant part of the losses is transferred from the second stage to the first. The losses of the second stage are reduced, but don't disappear completely. A simple change in the trajectory altitude from 70 to 148 km leads to gravitational losses, which, using the law of conservation of energy, are easily estimated with following formula:

$$\Delta v \approx \frac{g\Delta h}{< v >},$$

where Δv is the gravitational loss in the section of its acceleration trajectory that interests us, g is the acceleration of free fall, Δh is the change in the height of the trajectory, <v> is the average speed in this section of the trajectory.

From this formula it follows that the gravitational losses of Starship second stage are about 180 m/s. Add to this 100 m/s of control losses caused by the curvature of the trajectory, and we obtain an estimate of the total losses Δv ≈ 280 m/s, which is only 50 – 60% of similar losses of known expandable rockets. Then the total change in the characteristic velocity of Starship second stage will be 4.65 km/s, and its mass at this point will be equal to 365 tons.

This means that the thrust of the engines was below nominal, that is, the engines were throttled at this point, and the average degree of throttling is estimated from the ratios of the second stage mass determined by the two methods described above. It should be noted that the entire flight of the second stage took place with the power plant thrust below the nominal one. For example, the acceleration of the second stage at the start immediately after the staging was about 4.5 m/s^2, and the thrust of the power plant was approximately equal to 6 – 6.5 MN, which was around 0.4 of the nominal value. In this case, it is possible to throttle all six engines equally, or throttle only engines with a conventional nozzle, which have a slightly lower specific impulse at altitude. The latter option seems more reasonable where it is physically possible. The degree of throttling at the point of reaching a constant acceleration value in these cases will be equal to 0.83 and 0.64, respectively. Thus, the pressure drop across the oxygen pump at such throttling levels and at nominal pressure in pump inlet from a value of 170 [3, 4] is reduced to approximately 140 and 110, respectively.

III. Most likely cause of S25 second stage explosion on second flight

Now it is necessary to assess the fundamental possibility of Pogo occurrence in the mode under consideration, but accurate calculations are possible only after obtaining accurate information about the design of the stage, its flight mode and the operating modes of its engines.

It is assumed that when the second stage engines were started, the pressure in its tanks was quite close to the nominal value – 400 kPa. Acceleration with which it moved was increased, and, despite the decrease in the level of fuel components in the tanks, their hydrostatic pressure also increased and, therefore, the pressure at the inlet to the pumps of Raptor-2 engines also. In this regard, the power plant control system had to reduce the boost pressure at some point, and, judging by the release of boost gases at the 460th second, this was done at that time. As mentioned above, we will consider 2 throttling options at this moment: the main one, when only conventional Raptor-2 engines are throttled, and high-altitude engines operate at nominal mode, and the second – additional, when both versions of engines are throttled equally. We will also assume that after the boost gases are released, the nominal pressure in the tanks is restored. Then the pressure drop across the oxygen pump for vacuum engines will be $p_2/p_1 \approx 170$, for conventional engines – $p_2/p_1 \approx 110$, and in the second option for both of them – $p_2/p_1 \approx 140$, see Table 1.

The following notations are used 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 line from the pump to gas generator, L_2 is the length of the oxygen line 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.

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 Ship Raptor-2	170	0.310	3.00	3.310	19.9	11.7
	140				18.1	**12.8**
	110				16.1	**14.4**
	170	0.444		3.444	23.8	9.77
	140				21.6	10.8
	110				19.2	**12.1**

Since the own frequency of elastic vibrations of the second stage hull with a mass of 365 tons is estimated to be $f_e \approx 26.5$ Hz, with a multiplicity of 2 and the greatest possible difference in frequencies of about ± 8.5 %, Pogo excitation zone is located at the hydroacoustic frequency $12.1 < f_n < 14.4$ (Hz), and with a multiplicity of 3 – at $8.08 < f_n < 9.58$ (Hz). Then, with the length of the engine oxygen supply line $L_2 = 3.0$ m indicated in Table 1, this zone with a multiplicity of 2 corresponds to the values $0.310 < L_1 < 0.444$ (m), which seems to be quite reasonable values. In this zone, as can be seen from the table 1, Pogo is excited on conventional engines, but not on vacuum ones. In the case of an additional variant of throttling "Pogo zone" is shifted to lower L_1 values. When the pressure at the pump inlet was exceeded before the boost gases were released, the pressure drops on both versions of Raptor-2 engine were lower, and the own hydroacoustic frequencies of their oxygen supply lines were higher and outside "Pogo zone".

And after an almost instantaneous decrease in pressure in front of the pumps, the drop across them increased, the hydroacoustic frequencies decreased, and the engines of one version could fall into "Pogo zone" (in Table 1, at 0.310 < L1 < 0.444, engines with a conventional nozzle fell there), and the other – not fall. Or both engine variants could fall into "Pogo zone" – the conventional one with a multiplicity of 2, and the vacuum one with a multiplicity of 3. The analysis is also complicated by the fact that, most likely, the L_2 lengths of the oxygen supply systems in different engine variants were different. Therefore, we will limit ourselves to demonstrating the possibility of Pogo excitation after ventilation of tanks, and we will carry out specific calculations only after receiving all the information necessary for this.

After Pogo is excited, strong vibrations of the engines and pipelines began, leading to depressurization of the joints and the leakage of a certain amount of liquid oxygen. So the same occasion of "vented liquid oxygen", that E. Musk spoke about [2], occurs, but it was caused by an emergency that had already arisen in flight. The process began to grow exponentially, and by the 483rd second the engines stop working, and an explosion or even a series of explosions occurs, including due to the mixing of fuel components and its detonation. But the design of the stage was more or less preserved, and fell into fragments only more than a minute after that [3, 10].

What would happen if there was a sufficiently massive payload? In this case, obviously, everything could take a different path due to a change in stage elastic oscillations frequency. It is quite possible that then Pogo process would not have occurred at the end of the second stage acceleration. However, it is no less likely that it could have occurred at a different time and on a different section of the trajectory – all this must be calculated in advance so as not to guess before each launch – will Starship die today or on the next launch tomorrow.

Conclusions

1. The analysis shows that the explosion of the second stage of Starship during the second test flight occurred at the final stage of acceleration due to the emergence and development of self-oscillations of Pogo-type during hydroacoustic disturbances in the oxygen supply line of the engines.
2. Conditions conducive to the occurrence of self-oscillations were created during boosting gas was vented from oxygen tank of the second stage, due to a sharp change in pressure at the inlet of oxygen pumps of its engines when they were throttled.

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