# Cause of Super Heavy engines failures during static tests

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**Summary**

An assumption is made that the main reason for the failures which exceeding a reasonable number of seemingly well-tested reusable Raptor-2 engines during static fire tests of Super Heavy (Starship first stage) is, in principle, the same thing that led to accident of Starship on its first flight. This was self-oscillations of Pogo-type. However, due to the difference in the operating conditions of Super Heavy in flight as part of complex and at the launch position without a second stage, mechanisms for excitation of self-oscillations are different.

It is shown that the results obtained using the proposed process description model is consistent with what is observed in static fire tests.

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

**Symbol list**

c – speed of sound
D – diameter
E – modulus of elasticity
$f_n$ – frequency of hydroacoustic oscillations
$f_e$ – own frequency of rocket hull
k – rigidity of oscillation system
L – length
$L_{eq}$ – equivalent length of oscillatory circuit
m – mass
p – pressure
δ – wall thickness

## I. Introduction

It was demonstrated in paper [1] that on entire part of the trajectory where controlled flight took place, this rocket experienced sharp acceleration fluctuations with a period of 12 seconds, expressed in form of at least 10 pairs of narrow spikes, a sharp drop in acceleration to almost 0 at first, and then very sharp increase of it. This behavior of Starship is caused by previously unknown in rocket technology interaction of longitudinal self-oscillations of Pogo-type with rocket control system. These self-oscillations were excited by hydroacoustic disturbances in fuel lines of rocket engines. A numerical model had been created for calculating such hydroacoustic oscillations with pressure discontinuity at pump, and their interaction with own longitudinal vibrations of Starship hull have been analyzed. It was also shown that these intense longitudinal vibrations with a frequency of about 6 Hz were activated by hydroacoustic oscillations, frequency of which was on 3 or 4 times less, that is they had multiplicity 3 – 4.

It follows from the calculations results that engine throttling increases the frequency of hydroacoustic oscillations, and the response of the control system to intense Pogo-type oscillations – decreasing of engines thrust, transfer this oscillating system from the vicinity of initial multiplicity point to even more dangerous point of lower multiplicity, that led to a never before seen behavior of rocket system with the emergence of periodic double spikes of longitudinal acceleration, which ultimately caused Starship crash [1].

However, in that work the question of reasons for turning off the engines of power plant during the so-called static fire tests of Super Heavy, when all engines were started simultaneously, remained unexamined. Raptor-2 rocket engines used in this case were reusable, and therefore, before static fire tests, they could and should have been tested to the necessary and sufficient extent for operability and reliability on stands. However, when they worked together as part of Super Heavy power plant, a significant number of static failures happened, despite the fact that the duration of their operation in these tests was only 3 – 6 seconds [2 – 7]. Even NK-15 engines of N1 Soviet lunar rocket, quite hastily developed 6 decades earlier, which were disposable and, therefore, were not tested out before their launch in full configuration, of which there were almost the same number in the first stage – 30 versus 33 on Super Heavy, and which, together with KORD control system, are considered the main reason for the failure of this program, only in one case out of 4 did they begin to fail in such a short period of time – in the second launch [8].

Before first launch of Starship, only one such static fire test was carried out, and therefore, apparently, it was too early to draw any conclusions, without having the information that was known only to system developers. However, for the second flight in November 2023, in addition to one launch, 3 static fire tests have already been carried out, and, apparently, some preliminary conclusions can already be drawn. A total of 4 such tests were carried out by the end of 2023.

## II. Public information about Super Heavy static fire tests

So, we have available general information about four static fire tests of Starship first stage, called Super Heavy, presented in Table 1 (it also presents the same data from two flights conducted). This table uses the following notation:

A is number of engines that didn't turn on at the start;
B is number of engines stopped during ground test or in flight;
C is of them that may not have switched off completely;
Σ is the total number of engines that didn't operate for the entire planned time due to internal reasons.

**Table 1**

| N | Data | SH/Ship | Event | Duration (s) | A | B | C | Σ |
|---|---|---|---|---|---|---|---|---|
| 1 | 02/09/2023 | B7 | Test [2] | ~ 6 | 1 | 1 | 0 | 2 |
| 2 | 04/20/2023 | B7 | Flight [1] | ~ 100/145 | 3 | 5 | 2 | 8 |
| 3 | 08/07/2023 | B9 | Test [4] | 2.7 | 0 | 4 | 0 | 4 |
| 4 | 08/25/2023 | B9 | Test [6] | ~ 6 | 0 | 2 | 0 | 2 |
| 5 | 11/18/2023 | B9 | Flight [9] | 173/27 | 0/1 | 0/9 | 0/0 | 0/13 |
| | | S25 | | 322 | 0 | 3? | 0 | 3? |
| 6 | 12/29/2023 | B10 | Test [10] | ~ 10 | – | – | – | – |

During the first flight, all shutdowns occurred at approximately the 100th second; after the 145th second, when the rocket began to perform off-design maneuvers such as a "loop", it apparently became completely impossible to assess the condition of the engines. In static winter – autumn fire tests, from 1 to 4 engines were lost in 3 – 6 seconds, and their number even increased from February to August. The engine shutdown before launch was apparently caused either by the consequences of previous fire tests, including those with a smaller number of engines, or by random reasons. It seems to us that if engines that were previously tested quite well on the test bench are switched off with such a speed during full power plant tests, then there must be a reason why this is happening.

In the second flight (event No. 5) [9], operating time of B9 booster is divided into 2 phases: the first is the acceleration of Starship (173 s) and the second – braking and booster reversal (from restart of the inner ring engines to the explosion – 27 s). At the same time, 3 central engines didn't stop working from the start.

Flight of the second stage, which was quite successful for a long time, ended with an instant shutdown of telemetry, so that it was impossible to determine from it the causes of this incident. But it is quite obvious that it was an explosion of the engines. How many of them exploded? Since there were two groups of 3 engines each – regular Raptor-2 engines and Raptor-2 engines with a vacuum nozzle, also slightly different in location relative to oxygen tank, it is reasonable to assume that, most likely, 3 engines from that group exploded, which was less resistant to the explosive process. A more accurate conclusion can be made if the exact drawings of the second stage power plant are known.

At the very end of the year, 12/29/2023, after first unsuccessful attempt to do this on 12/21/2023, the fourth static test was carried out with B10 booster (event No. 6) [10]. Unlike all previously conducted tests, judging by the image of the booster, an intermediate interstage compartment for hot staging was installed, which helped in the second flight suppress self-oscillations of the Pogo-type when flying as part of a complex of two stages. But the hope for it when testing only the first stage looks very strange. Also, for the first time, number of engines that stopped during this test wasn't reported within a week after it was carried out. Therefore, in Table 1 in the last line there are solid dashes only. Apparently, SpaceX transparency policy has changed dramatically since mid-December 2023.

### III. Probable cause of Super Heavy's engines failures during static fire tests

If in the flights of Starship almost all the troubles were caused by Pogo-type oscillations, then it is natural to try to apply this model and to static tests. However, flight conditions and test conditions are fundamentally different:

- the rocket stands on the ground and does not fly in the air;
- instead of assembly of two stages, only the first was located at testing position.

Pogo-type oscillations in flight were detected by direct observations during launches of V-2 (A-4) rocket during its tests at Peenemunde test site, when they were weak and did not cause any serious problems. But author of this work had absolutely no data on oscillations of this type during tests on the ground until mid-November 2023. However, this may be expected, since before the development of reusable rocket systems and when using rocket engines that could typically only be fired once, static fire tests would seem almost never were conducted. However, it was suggested that self-oscillations may be quite expected. As a result, the first version of this paper was written, describing the probable cause of Super Heavy engine failures during static tests.

However, in mid-November, data on the order in which the engines of Saturn V first stage S-1C were turned on at launch became known from a source [11]. These engines were not turned on simultaneously, but in the following order (see Fig. 1): first – the central engine 5, further a pair of diametrically located engines 1 and 3 was turned on, and then the remaining pair of engines – 2 and 4. All this time the rocket continued to remain on the ground. But immediately after turning on the central engine, an elastic wave passed through the rocket hull, which were provoking occurrence of hydroacoustic disturbances in the fuel lines of engines 1 – 4, which, in the absence of suppressing means, led to the appearance of self-oscillations of Pogo-type during the second launch (SA-502), which, judging by these data, they began on the ground and continued in the flight.

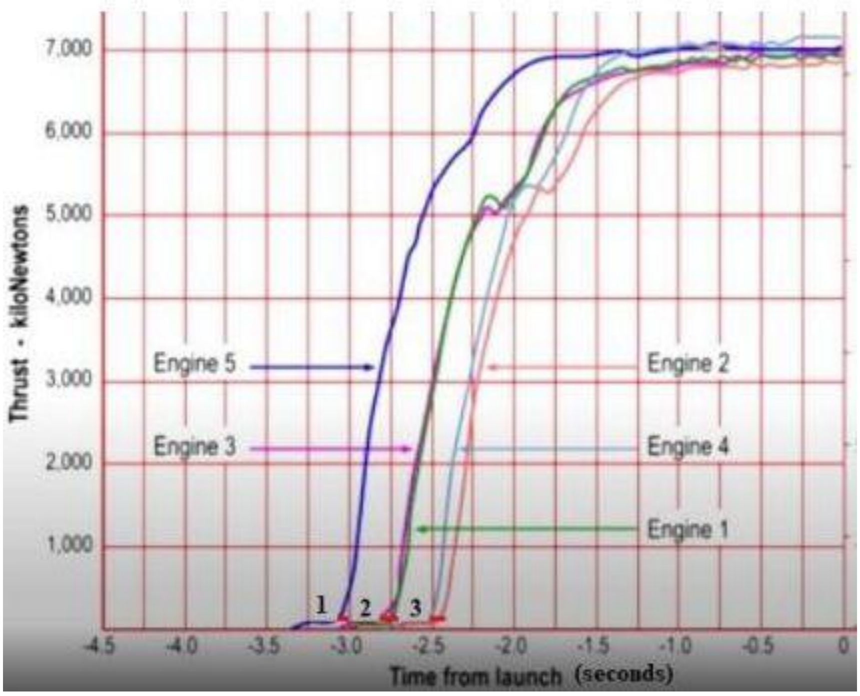


**Fig. 1 – Thrust profile of S-1C first stage engines of Saturn V rocket (SA-506) during launch**

Thus, it was experimentally confirmed that self-oscillations of Pogo-type can also arise when the rocket is still on the ground. And only by using means of hydroacoustic perturbations suppressing in fuel lines can we hope that there will be no Pogo, see Fig. 1, which shows the increase in thrust at the start of five engines of Saturn V rocket (SA-506), which sent first expedition to the Moon on Apollo 11. They were there then.

This is neither the time nor the place to engage in a deep analysis of the differences in the boundary conditions imposed on the oscillation processes of a rocket vehicle in flight and on the ground. Let's simply take it for granted that these differences do not introduce qualitative changes into these processes, and let's try to apply the method, already to a certain extent proven for "flight", to the "ground".

In accordance with the second point of the main differences list between these processes, own frequencies of Super Heavy's oscillations differ from own frequencies of Starship. So mechanism for excitation of self-oscillations described in paper [1] due to interaction of disturbances in methane line of this stage and vibrations of its hull cannot works. We need to look for something else.

## IV. Estimates of own Super Heavy hull longitudinal vibrations' frequency and hydroacoustic oscillations in oxygen line of the rocket

First, we will determine the own frequency of Super Heavy, using the method described in paper [1] and, judging by the results obtained there, quite acceptable for preliminary estimates. As before, we use the formula for calculating elastic longitudinal vibrations $f_e$ of a rod with a fixed end and a load at its other end, in the case when the mass of the elastic rod is negligible compared to the mass of the load:

$$f_e \sim \sqrt{\frac{k}{m}} \ ,$$

where k is the rigidity of the oscillatory system, m is its mass. In the case of a rocket stage on the ground, the application of this formula seems even more justified than before.

In the case of thin-walled pipe vibrations, of which this rocket stage essentially is, this formula can be reduced to the following form:

$$f_e \sim \sqrt{\frac{\pi E D \delta}{m L}}\ , \qquad (1)$$

where E is the elastic modulus of the material, D is the diameter of the pipe, δ is the thickness of its wall, m is the mass of the stage, L is its length. Sign ~ means that the frequency is recalculated from experimental data available for Saturn V rocket, which, however, has very little effect on the result, since the proportionality coefficient in estimating its natural frequency turned out to be close to 1 [1].

The elastic modulus of 304L stainless steel, from which Super Heavy hull is made, is E = 193 – 200 GPa [12]. Its length is 69 m, however, due to the subtraction of Raptor-2 engines height and the distance from them to the support washer to which they are attached, it is assumed that the length of the elastic oscillatory element will be approximately 65 m (see [1]). Its diameter D = 9.0 m, steel wall thickness δ = 4.0 mm, stage mass m = 3.6 kt. If the fuel filling of the stage was incomplete, and its mass was less, then, as shown below, this would only lead to the fact that self-oscillations would be excited at lower engine thrust.

Then the own frequency of Super Heavy hull can be estimated as $f_e$ = 9.65 – 9.8 Hz, despite the fact that the own frequency of the entire Starship system, according to work [1], was 5.8 – 6.25 Hz. After this, it was enough to recall the frequency of hydroacoustic oscillations in the oxygen line of the stage from the same work to make sure that the coordination of these frequencies for the first stage during static fire tests is good, see Table 2.

**Table 2**

| **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 |

In it, c is the speed of sound in liquid cryogenic oxygen, $p_2/p_1$ is degree of pressure increase in oxygen pump of Raptor-2 engine, $L_1$ is length of oxygen line from the pump to the gas generator, $L_2$ is the length of the oxygen line from tank to the pump, $L_3$ is their sum, Leq is effective length of the oscillatory circuit, that is, the length that corresponds to the frequency of oscillations that arise in it in the absence of a pump, $f_n$ is the frequency of hydroacoustic oscillations on the liquid oxygen line.

Since the frequencies of hydroacoustic oscillations in the oxygen line of the engine at its nominal thrust (at maximum pressure drop across the pump) for two possible lengths of the oxygen path $L_1$ = 0.5 – 0.4 m ($f_n$ = 9.2 – 10.3 Hz) are close to the own vibration frequency of Super Heavy's hull ($f_e$ = 9.65 – 9.8 Hz), then it can be assumed that elastic waves traveling in such a long structure can excite self-oscillations of Pogo-type even when it is not in flight, but is standing on the ground. It turns out that in this case, self-oscillations can occur in it, but, unlike a complete rocket assembly, they are realized through hydroacoustic oscillations of not methane, but oxygen line of the fuel system (which is a more common situation for rockets with an oxidizer – liquid oxygen).

As was shown in paper [1], the frequency of hydroacoustic oscillations varies approximately inverse proportionally to the square root of the pressure drop across the pump. Therefore, it turns out that engine failure during tests should occur at the moment its thrust approaches the nominal one, which, as far as can be judged from the available data, is quite true.

## Conclusions

Thus, the characteristics of Super Heavy are such that when it is part of all Starship system, self-oscillations of Pogo-type are excited in it with a frequency of about 6 Hz through the disturbances in the liquid methane line, and when it works without a second stage, their frequency is about 9.5 – 10 Hz, and they are excited through disturbances in the liquid oxygen line. And in both cases, these self-oscillations lead to the stopping of its engines.

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