Mechanism of Starship first stage explosion during its return maneuver

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The Lord is sophisticated, but not malicious.
A. Einstein

Summary

There is shown how the influence of factors external to power plant of Starship first stage (booster) on the frequency of own hydroacoustic oscillations in oxygen supply line of the engine determines the possibility or impossibility of longitudinal self-oscillations excitation of Pogo-type in the booster.

It has been demonstrated also that the numerical model presented here of a two-stage process with a variable frequency of hydroacoustic oscillations fully explains all 7 of its visible features that preceded explosion of the booster during boostback – braking when performing a return maneuver.

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

Symbol list

c – speed of sound
f_e – own frequency of rocket hull
f_n – frequency of hydroacoustic oscillations
g – acceleration of gravity
L – length
L_{eq} – equivalent length of oscillatory circuit
m – mass
p – pressure
w – linear acceleration
ε – angular acceleration
Δ – difference
ω – angular velocity

I. Introduction

Causes of explosions that ended flights of Starship both stages after their separation and almost complete acceleration of the second stage was examined in paper [1]. Both incidents were explained there by excitation of self-oscillations of Pogo-type due to design features of both rocket system itself and its power plant. Episode with the explosion of the second stage was quite simple to investigate and was described to a fairly complete extent in the paper [1].

But the explosion of the first stage – Super Heavy B9 booster during the return maneuver – boostback turned out to be much more difficult to understand, primarily due to the fact that it was the most complex dynamic maneuver of all that were implemented during that two flights of Starship. In addition, quantitative values of the boostback key parameters, as well as the characteristics of the main booster systems during its implementation, are essentially almost unknown. In addition, calculations of the hydroacoustic oscillations frequencies according to the previously developed theory (see [2]), necessary for analysis of self-oscillations excitation, are accurate for quasi-stationary states of the engine and its fuel system. But this didn’t happen during the boostback.

II. Main characteristics of boostback performed by booster during the second flight of Starship

Several different cases of Pogo-type longitudinal self-oscillations occurrence in Starship were considered in papers [1 – 3]. In situations where these oscillations had enough time to fully manifest themselves, they destroyed this rocket vehicle or its individual stages three times in two flights. But, in those cases when Pogo process arose during a short-term transition process, for example, when rocket engines reached the nominal stationary operating mode, in which there were no longer conditions for its development, then it spontaneously died out [1]. In all fairly fully considered cases, Starship or its stages were either on the ground, or, although they were flying, the main parameters of its trajectory changed slowly, that is, with a low speed compared to the speed of processes occurring in the engines and in fuel system. So at any given moment in time, to a first approximation, it could be assumed that the conditions in which the engines were worked are constant. This is exactly how the possibility of Pogo occurrence was assessed in works [1 – 3].

During the first 55 – 60 seconds, the acceleration of Starship varied slightly in the range of 5 – 6 m/s^2, and then for 100 seconds it slowly increased to approximately 16 m/s^2, (see Fig. 1) [4, 5], Acceleration components, associated with slow changes in the position of rocket hull in space relative to its center of mass, were very small even in absolute value. So, with the characteristic period of Starship hull own oscillations at IFT-2 being about 0.1 seconds, the quasi-stationary approach to Pogo calculations was completely justified. However, at the initial stage of the return maneuver, changes in dynamic characteristics occurred very quickly. When Starship first stage (booster) B9 in the second flight (IFT-2) after successful separation of the second stage (Ship) began to perform a return braking maneuver (boostback), then, as can be seen from Fig. 1, the booster acceleration (thick yellow line) obtained in this graph by differentiating the speed shown in the video began to change extremely quickly. In this mode, in contrast to the acceleration stages, when the pitch angles are small and in a first approximation it isn't possible to distinguish between total and longitudinal accelerations of the vehicle, it is necessary to take into account not only the acceleration module, but also its direction, which changes to the opposite during boostback.

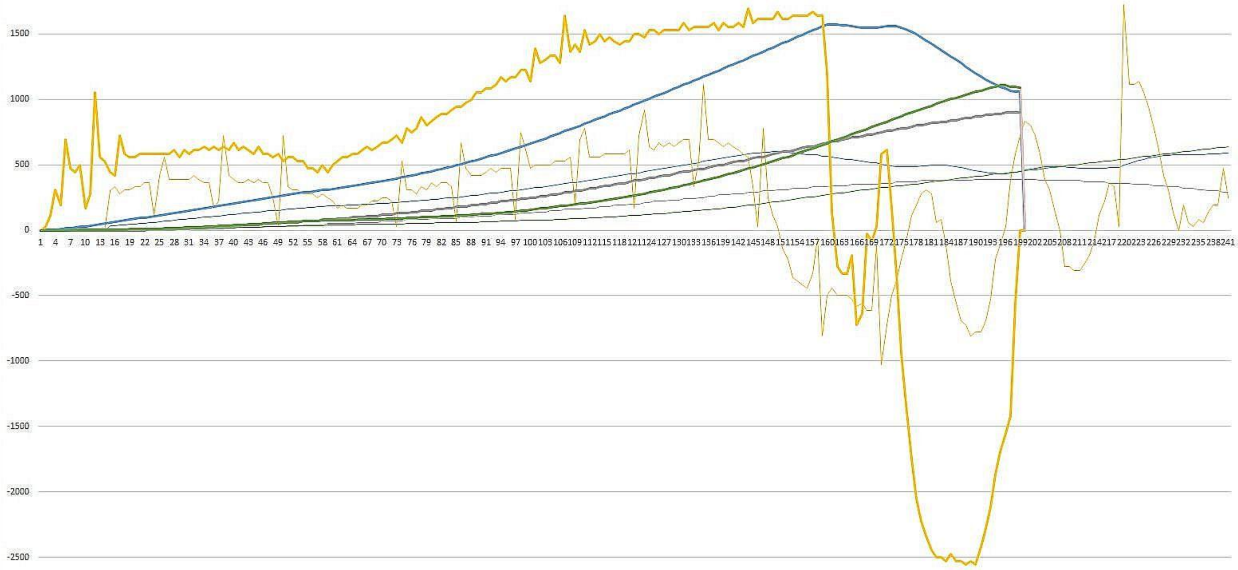

Fig. 1 – Acceleration, speed, altitude and range of Starship in the first and second flights [4]

In Fig. a comparison was made (see [4), where a comparison was made over time (in seconds) of four Starship parameters in two flights, namely: rocket acceleration (in cm/s^2), speed (in m/s), altitude (in hm), as well as direct (horizontal) flight range (also in hm). Data related to the second flight (IFT-2) is displayed with thick lines, and data related to the first flight (IFT-1) is displayed with thin lines. Acceleration is shown with yellow curves, speed with blue lines, altitude with olive lines, and range with purple lines.

When analyzing booster characteristics during the return maneuver, it should be taken into account that in Fig. 1, all accelerations are presented in the original coordinate system. But, as will be shown below, at a time interval of approximately 170 – 180 seconds, booster rotated around its transverse axis by 180° (see Fig. 2, 3), and in its own coordinate system, accelerations and overloads changed signs.

As can be seen from Fig. 3, by the moment of time shown on it (by 183 seconds, or, more precisely, 5 seconds before that), 3 of the engines restarted during the turn of the stage had already turned off, and all of them, together with the fourth, which didn't turn on, ended up on the same side of the booster.

After turning off 30 of the 33 booster engines, its acceleration (in conjunction with the second stage) by approximately 160th second of flight, that is, by the time of hot staging, drops firstly to 0, and then after 9 – 10 seconds relatively small negative values (or just around zero values – you can't be sure in this short section of the trajectory in accuracy of data concerning acceleration) up to until the inner ring engines are turned on again and, at the same time, the booster turns, begins to quickly increase to +25 m/s^2 (in own booster coordinates system). It should be noted that 9 out of 10 booster inner ring engines turned on. However, immediately, in the time interval from 174 to 178 seconds, the first 3 of the 12 operating engines were switched off, beginning with one of the central engines, which had previously operated without stopping from the very start. However, from 170th to 179th – 180th seconds, the acceleration of the booster nevertheless increased to +25 m/s^2, and it itself turned around its transverse axis by 180° relative to the position it occupied at the moment of staging.

Fig. 2 – The moment of stage separation, the longitudinal axis of the booster approximately coincides with the direction of system flight

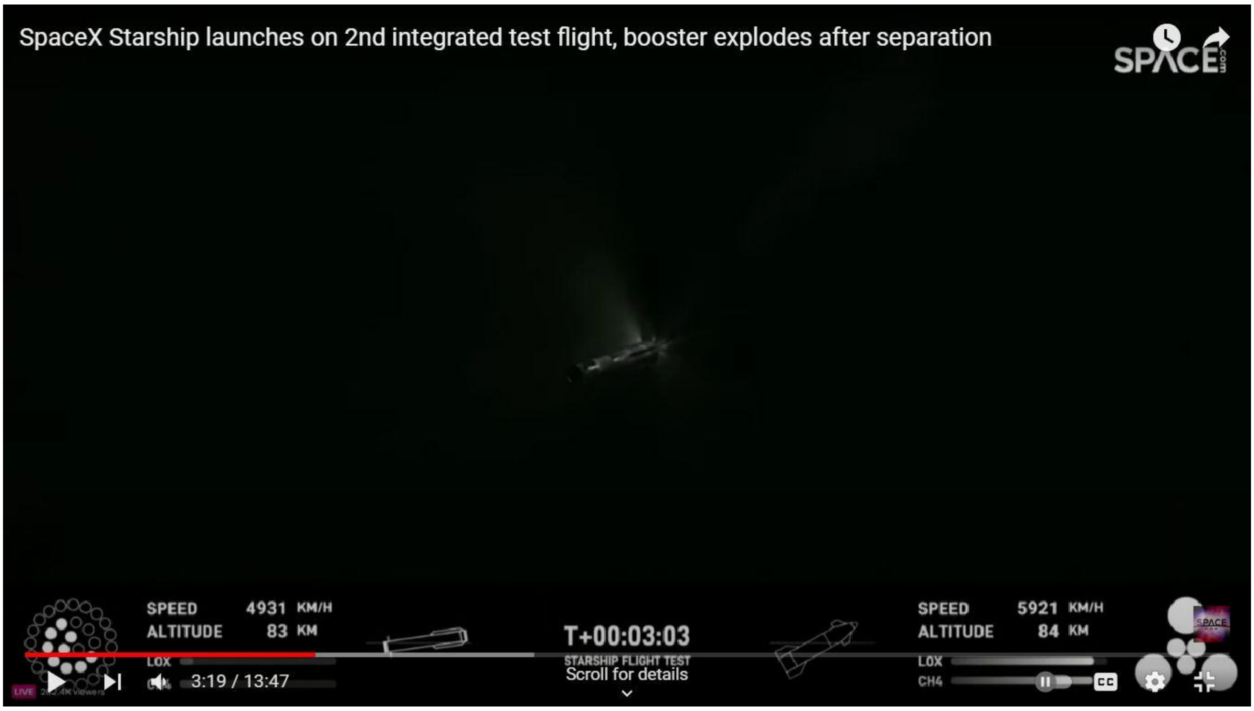

Fig. 3 – Booster made half a revolution around its transverse axis, turning around to return to the start vicinity

Then, the braking mode began without sudden maneuvers and changes in parameters of power plant, which, according to the plan, with 13 operating engines, was supposed to last up to 227th seconds [1]. But, in fact, 9 engines worked on it for only ~10 seconds, and then in 6 seconds, from 191th to 197th seconds, they all turned off. At the same time, at 194th and 197th seconds, 2 powerful lateral flame emissions were noticed from the same area of the engine compartment, and all this ended with the explosion and destruction of B9 stage at the beginning of the 200th second of flight [5], see Fig. 4.

Fig. 4 – View of the sky one second after the first stage explosion

Of course, accuracy of determining the accelerations presented in Fig. 1 at moments of rapid changes in the speed and position of the booster in space, in connection with the way they were obtained, may raise certain doubts. The same, if not to an even greater extent, applies to data on the spatial position of the booster, taken from "flat" video frames, as well as to the iconography of starting and shutting down engines – it may diverge by 1 – 2 seconds from what is directly visible in the frame. However, as the following shows, for a fundamental solution to the problem of why B9 booster exploded, as part of a preliminary consideration, they can be used. And after that, let SpaceX engineers, having all the telemetry information, turn this half-qualitative solution of the problem into a quantitative one to refine their systems and algorithms.

III. Estimates of boostback dynamics quantitative characteristics and parameters of booster power plant

Now we need to obtain reasonable estimates of overloads experienced by the booster engines and their oxygen supply lines, since preliminary calculations have shown that in the second flight of Starship (at IFT-2), unlike the first (IFT-1), all problems associated with self-oscillations like Pogo arose there. In addition, changes in tank pressure caused by these overloads should be assessed.

First, let's determine the angular acceleration ε when booster rotates during a turn. To a first approximation, we will assume that for half of the turn time (5 – 6 s) booster rotated with constant acceleration, and for the second half of the time it was decelerated with the same absolute angular acceleration. Then its estimate, taking into account the fact that the maneuver was probably spatial and not flat, will be $|\varepsilon| \approx 0.1$ rad/s^2. The initial and final angular velocities were zero, the maximum velocity was about $\omega \approx 0.45$ rad/s, and the average during the entire turn was about $\omega \approx 0.225$ rad/s.

From IFT-2 video iconography [5] it follows that by that time about 12 % of fuel remained in the stage. This means that in lower booster tank – a tank with liquid oxygen, where the bulk of the propellant component was located, the thickness of the oxygen layer, taking into account curvature of lower bottom, was about 4.5 m. It was here, as well as in the engine compartment, that the bulk of the booster mass was concentrated, beyond with the exception of the mass of liquid methane layer in upper tank at a distance of at least 45 – 50 m from the lower edge of the booster, as well as the mass of the hull, more or less evenly distributed along its length, which, as is known, is about 70 m. In this case, mass of the remaining methane should have been about 0.28 by mass of the remaining oxygen. In addition, top cover of the methane tank and interstage hot separation compartment (FHSI) weighing 9 t located at the very top end of the booster are also important for the estimates. Apparently, it will not be a big mistake if we assume that, taking into account the mass of booster hull, its center mass is located approximately 15 m from the area of interest to us – the vicinity of the turbopumps of Raptor-2 engines oxygen line. We will leave more accurate calculations to those who are supposed to do this according to the staffing schedule.

Then the average centrifugal acceleration in the zone of interest to us will be ~ 1 m/s^2, and the tangential acceleration from spinning the booster will be about 1.5 m/s^2. These values are quite small compared to the longitudinal acceleration values shown in Fig. 1 and reaching up to 25 m/s^2 in quasi-stationary segment of flight with braking. Since the estimate of centrifugal acceleration is about 4 % of this value, it can be completely neglected in a first approximation. But the tangential acceleration, directed normal to the vector of the main, longitudinal acceleration, despite its relatively small value – about 6 % of it, is the source of effect that can be observed in video [5] – engine shutdown, asymmetrical relative to the longitudinal axis of the booster, well visible, for example, in Fig. 3, so we will take it into account explicitly.

Based on the available data, we will determine the operating mode of the engines during the quasi-stationary flight segment, which began after completion of booster turn. At the moment of staging, mass of the first stage was estimated to be about 0.60 kt (0.20 kt – the mass of the structure + 12% of the initial amount of propellant). When the propellant consumption of Raptor-2 engine at nominal operating mode is 0.685 t/s [6], 9 engines will consume about 50 tons of propellant in 8 seconds. Based on the mass of booster and its longitudinal acceleration at the beginning of the quasi-stationary flight segment, we will determine the thrust of the power plant during braking, degree of its throttling and, accordingly, the specified mass fuel consumption. After 3 – 4 iterations at acceleration $w = 25\ m/s^2$, by the 180th second we obtain the booster mass $m \approx 0.565$ kt with a power plant thrust of $T \approx 14.1$ MN and a pressure throttling degree of the engines of about 0.70. If all 13 engines worked as planned, then the acceleration of booster at this moment would have been slightly more than 36 m/s^2. Let us remember that for the second stage during its acceleration there was a limitation of $w \leq 35\ m/s^2$ [1], and we will proceed from the fact that the planned maximum acceleration of booster should also not exceed this value.

After this, we need to evaluate how the pressure at the inlet to the oxygen pump of the engines changed before the boostback and during its implementation. The nominal inlet pressure to both pumps of Raptor-2 engine is 400 kPa, see fig. 5 [6].

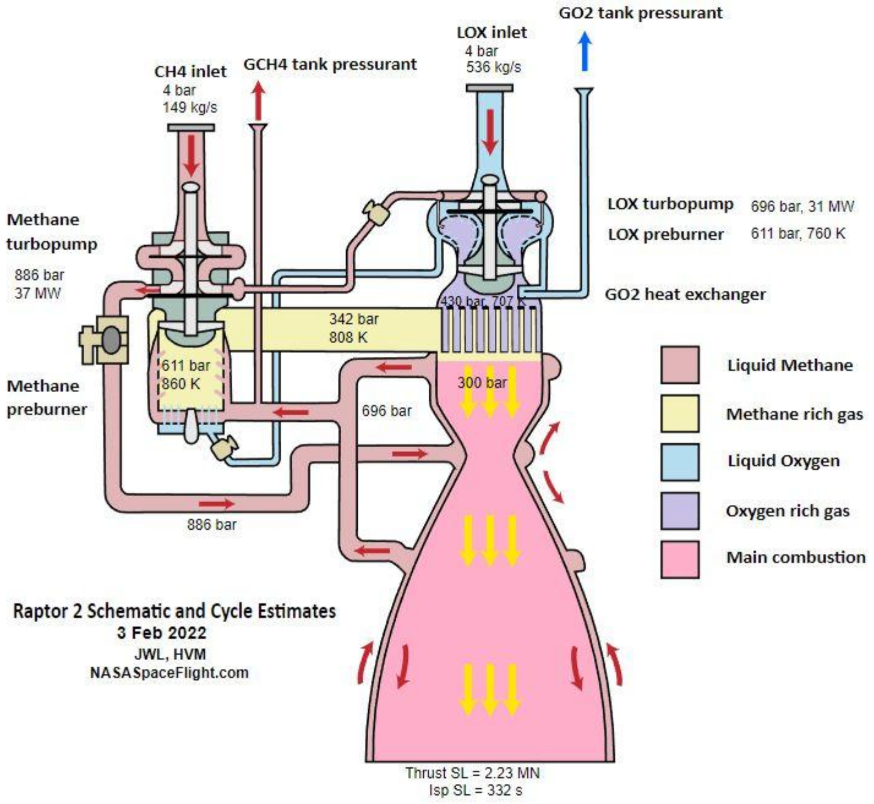

Fig. 5 – Raptor-2 engine diagram [6]

It is ensured by two factors – hydrostatic pressure of the liquid fuel layer in the tanks and pipelines supplying propellant components to the pumps, as well as gas boost pressure in the upper part of the tanks that isn't filled with propellant. The pressurization of the tanks in both stages of Starship is autogenous. This means that the gases for boost are taken from their main flows behind turbines of both gas generators and, after reducing the pressure in throttle and the temperature in heat exchanger, they are supplied to the corresponding fuel tanks: from the oxygen circuit to the oxygen tank, and from the methane circuit to the methane tank. And the total of both these pressure components should be about 400 kPa. This is apparently quite easy to achieve with slow changes in flight parameters. But with boostback the situation is completely different.

At the final phase of the first stage acceleration, it was 15 – 16 m/s^2, then already on the separated booster it was in the vicinity of 0 for about 10 seconds, and then in about 6 – 8 seconds according to the flight program, from our estimates, it should have risen up to 35 m/s^2.

At the moment the inner ring engines were restarted, the thickness of the oxygen layer was at least 4.5 m, and the supply pipelines were located mainly normal to the longitudinal axis of the booster [7]. At this time, the oxygen was unlikely to be already supercooled; in addition, the pressure in the tank was changing, so at a first approximation, we will assume that the oxygen density was unchanged – $\rho \approx 1.14$ kg/m^3. Then its hydrostatic pressure would drop from ~ 80 kPa to 0 over the course of 16 – 18 seconds, and would immediately increase to 180 kPa, that is, it would reach approximately half of the required total pressure in the tank.

Despite the fact that the density of methane $\rho \approx 0.415$ kg/m^3 was 2.75 times less than that of oxygen, its hydrostatic pressure during boostback changed much more strongly, since the methane tank is located above the oxygen tank, and to the height difference between the upper surface of liquid methane and pumps, it is necessary to add height of the oxygen tank, which is not less than 33.4 m (see [1]). Therefore, the thickness (height) of the methane layer cannot be less than 35 m even at the moment of flight that interests us. Then its hydrostatic pressure under the above conditions from ~ 230 kPa would drop to 0, and would immediately increase to 510 kPa, which would be 27.5 % even higher than the nominal total value. It should be remembered that, judging by previous tests on hydraulic fracturing of tanks, the maximum permissible pressure there should not exceed 600 kPa. In reality, due to the fact that only 9 engines out of 13 were fully turned on, the booster acceleration increased to 25 m/s^2 only, and the hydrostatic pressures of oxygen and methane in the quasi-stationary segment of return trajectory turned out to be equal to ~ 130 kPa and ~ 365 kPa.

It is possible that if all 13 engines were running, the degree of throttling would be higher than during IFT-2. But, in any case, it is clear that before restarting buster engines, in order to prevent rupture of the propellant tanks, it was necessary to greatly and quickly reduce the boost pressure, especially in the methane tank. This could only be done by venting the boost gases into the external space. And on the second flight it was actually done. The video frames clearly show how, in the interval of 163 – 168 seconds, a huge "flower" suddenly "bloomed" around Starship, see Fig. 6. It was formed by tiny droplets of water, condensed after the expansion of boost gases almost into a vacuum, as well as, possibly, droplets of methane and oxygen, and "snowflakes" of carbon dioxide. For some reason, few of the countless number of commentators paid attention to this bright spectacle. This pressure release stopped 1 second before stage staging began. It may be noted that a faint resemblance of this phenomenon was once again observed around the second stage at 460th seconds of flight.

Fig. 6 – Removal of boost gases from fuel tanks before staging beginning

It should be assumed that during a sufficiently long operation of the power plant on a quasi-stationary segment of the return trajectory, the pressure at the inlet to the pumps should be nominal, that is, 400 kPa. Then, from previous estimates, it can be determined that at the moment the engines began to operate again at about zero acceleration, the boost pressure in the oxygen tank should have been about 220 kPa.

From all this it follows that on a quasi-stationary segment of the trajectory, pressure drop across the oxygen pump instead of 170 at nominal mode with the throttling degree computed above of 0.70 will decrease to 120. But when these engines are started at the inlet pressure around 220 kPa, this pressure drop at the same operating mode engine would be approximately 220. Conditions in the methane supply line of the engines changed even more. Thus, during the restart, conditions in the areas varied greatly, which clearly made it difficult for the engines to start operating. However, 9 out of 10 of them turned on, but 3 immediately, after 4 – 8 seconds, stopped working. A complete analysis of what happened to them is now impossible under these conditions; however, it seems to us that an approximate model of this process that explains it through the double excitation of Pogo would be very useful. Moreover, as further calculations showed, these 2 self-oscillatory processes could be realized with quite reasonable values of the main characteristics of engines and fuel lines. And their development down to the smallest details coincides with the visible picture of what happened.

IV. The most likely cause of a booster explosion during a return maneuver

So, we believe that in the quasi-stationary segment, shortly after the beginning of which there was a second and landslide shutdown of nine booster engines, which ended in an explosion, the throttling degree of the engines was equal to 0.70, and then the pressure at the inlet to its oxygen pump was 400 kPa. In this case, the pressure drop across the pump, one of the most important parameters determining the frequency of hydroacoustic disturbances, is $p_2/p_1 = 120$. A softer process of the first shutdown of three engines when the booster power plant is brought to a quasi-stationary operation mode will be considered as a first approximation at average values of pressure at the inlet pump, varying, as follows from the above consideration, from approximately 220 kPa to 400 kPa, that is, at 310 kPa. In addition, let us remember the tangential acceleration from the booster spin, which was ~ 1.5 m/s^2, and with a distance from the center of the booster to the locations of the inner ring engines equal to ~ 3 m, we obtain differences in the hydrostatic pressure of liquid oxygen at the inlets to the pumps of these engines $\Delta p \approx \pm 5$ kPa on "front" and "back" sides of the booster rotation. So, we estimate the pressure at the inlet to their pumps to be 305 kPa and 315 kPa. In this case, the pressure drops across the pumps in these cases will be equal to $p_2/p_1 \approx 160$ and $p_2/p_1 \approx 155$.

The length of the oxygen lines from the pump to the gas generator L_1, as before, see [1 – 3], will be assumed to be equal to one of three values: 0.30 m; 0.40 m and 0.50 m. The length of the oxygen line from the tank to the pump L_2, after reviewing the information received just a few days ago (see [7]), we must increase to 4.0 m compared to the previously used typical value $L_2 = 3.0$ m. This will slightly reduce the frequencies calculated earlier in [1 – 3], but this shift can be easily compensated by a slight decrease in the calculated value of L_1. However, for the central engines, and, possibly, for the outer ring engines, the real value of L_2 may turn out to be close to 3 m. So, without focusing on the exact quantitative values of the parameters that determine the frequencies of hydroacoustic disturbances (especially since these values are not available to us), we will try to identify the qualitative structure of the resulting numerical solutions.

It should also be recalled that in the episode under consideration, the own frequency of elastic oscillations f_e of B9 booster was estimated at 18.4 – 18.7 Hz [1]. For simplicity, we take the average value $f_e = 18.55$ Hz, and we assume that Pogo process is possible if the frequency of hydroacoustic disturbances (including taking into account the multiplicity) differs from this value by no more than ± 8.5 %. That is, with a multiplicity of 2, the process of self-oscillations should have occurred at hydroacoustic frequencies of $8.55 \le f_n \le 10.1$ (Hz), and at resonance (that is, with a multiplicity of 1) – at $17.1 \le f_n \le 20.2$ (Hz).

In accordance with the above values of the defining parameters, calculations were carried out of the own frequencies of hydroacoustic disturbances during first boostback phase, partially implemented in IFT-2, 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 (v)**	**L_{eq} (m)**	**f_n (Hz)**
c = 930 m/s						
Starship Super Heavy Raptor-2	160	0.30	4.00	4.30	22.1	10.5
	155				21.7	10.7
	120				19.2	12.1
	160	0.327	4.00	4.327	23.0	***10.1***
	155				22.7	10.3
	120				20.0	11.6
	160	0.40	4.00	4.40	25.4	**9.16**
	155				25.0	**9.30**
	120				22.1	10.5
	160	0.436	4.00	4.436	26.5	**8.78**
	155				26.1	**8.91**
	120				23.0	***10.1***
	160	0.474	4.00	4.474	27.6	8.42
	155				27.2	***8.55***
	120				24.0	**9.70**
	160	0.50	4.00	4.50	28.3	8.20
	155				27.9	8.33
	120				24.6	**9.45**

First, frequencies were calculated at $L_1 = 0.30$; 0.40 and 0.50 (m), and then those values of this parameter were determined at which frequencies first fall into Pogo excitation zone when starting the inner ring engines ($L_1 = 0.327$ m), then when operating in a quasi-stationary section ($L_1 = 0.436$ m) and when exiting Pogo mode when starting the engines ($L_1 = 0.474$ m), the corresponding boundary for the quasi-stationary mode lies at parameter values outside the computational domain, at $L_1 \approx 0.58$ m. Bold font in Table 1 shows frequencies falling within Pogo excitation zone (with a multiplicity of 2), oblique bold font – these is their boundaries by frequency ***8.55*** **< fn <** ***10.1*** (Hz).

But, as can be seen from Table 1, Pogo processes simultaneously in both phases of the boostback in the considered variant of parameters ($L_2 = 4.0$ m) could only occur at $0.436 < L_1 < 0.474$ (m). For other values of p_2/p_1 and L_2, these boundaries should shift slightly. Since for the central engines and the inner ring engines the values of L_2 parameter in reality should be somewhat different, the dimensions of the intersection zone of geometric Pogo excitation regions will turn out to be larger, and the real picture of these processes may be more complex. However, without exact data, we will limit ourselves to the simplified picture presented in Table 1.

Of course, all these estimates are very approximate, but they, nevertheless, prove the fundamental possibility of the occurrence of Pogo processes during a boostback, and, if you are especially unlucky, then there can be up to four such processes differing in excitation frequencies, due to the possible difference the oxygen lines lengths for the center and inner ring engines, as well as due to the two phases of engine operation during boostback.

It is apparently worth mentioning one more aspect of the operation of closed-cycle engines operating on a gas-to-gas scheme, like Raptor-2. In this scheme, small amount of fuel from the corresponding pump is supplied to the oxidizer gas generator and vice versa, see, for example, Fig. 5. In this case, naturally, connections arise between the engine fuel and oxidizer supply circuits. Moreover, in both circuits these feedbacks turn out to be positive, and these circuits become fundamentally unstable.

The first attempt to create such an engine (RD-270) was made in the Soviet Union at OKB-456 more than half a century ago. Interesting, but very sparse information about this can be found from sources [8 – 10]. They reported that "due to the presence of two gas generators (pre-combustion chambers) and 2 TPUs [turbo-pump units], which went into one chamber [main combustion chamber of the rocket engine] and operated in parallel, low-frequency pulsations were observed in the gas generator and chamber. The main problem [was] synchronizing the joint work of two TNAs. The TNAs tried to overpower each other; it wasn't possible to stabilize them without help of a BCVM [high-speed digital computer]" [8]. Thus, the instability of such a scheme has been demonstrated in practice.

Raptor-2 engine operates successfully, since positive feedback between the fuel and oxidizer circuits was suppressed using computer control, and the statically unstable system became dynamically stable. Therefore, it is quite justified to consider hydroacoustic disturbances in these contours independently of each other, which was done when constructing all the calculation models described in articles [1 – 3].

V. Seven observed special features of the process that occurred with booster during return maneuver, which directly follow from the constructed model of double Pogo excitation

The process that occurred with booster during return maneuver had at least 7 specific features visible on the monitor with the naked eye that should be explained by the model that claims to describe it. They can be characterized as follows:

1. The presence of two clearly separated shutdown phases of booster engines.
2. Not turning on one and turning off three engines during the process of restarting.
3. The location of all failed engines at this phase of boostback is on one side of the booster only.
4. Reaching stable operation of the remaining engines by the end of their startup process.
5. Unexpected shutdown of all engines remaining in operation in the quasi-stationary boostback segment after some time.
6. First slow, and then an avalanche-like development of this process.
7. Completion of this process with an explosion.

If we assume that the process of Pogo development took place, and in the numerical model presented in the previous section of the work we believe that the length of the oxygen line from the pump to the gas generator was approximately $L_1 \approx 0.43$, then all these 7 features become direct consequences of the structure of this model.

Explanation of the observed features of the process within the framework of "Pogo model":

1. Two phases of engine shutdown are caused by different levels of pressure entering the engines' oxygen pumps during these periods of time. By the time the engines started turning on after the boost gas releasing from tank before the staging, the pressure in it was not much higher than half of its nominal value. Therefore, despite the rather high degree of throttling of the engines, the pressure drop across the oxygen pumps was estimated to be close to the nominal, or, at first, even possibly exceeding it. As a result, the frequency of hydroacoustic disturbances was deep in Pogo excitation zone, and this process immediately began to develop rapidly after the engines started. By the beginning of the second phase (the beginning of the quasi-stationary phase of the boostback), the previous increase in the longitudinal acceleration of the booster due to 9 operating engines led to an increase in hydrostatic pressure in the tank, and the control system using autogenous supercharging brought the pressure in it to nominal (which would not need to be done with 13 engines running). Therefore, the frequency of hydroacoustic disturbances increased, reaching the border of "Pogo zone" or even slightly crossing it. At the same time, the racing of Pogo became either very slow or stopped altogether.
2. After turning on the engines again, due to the fact that the frequency of hydroacoustic disturbances was deep in Pogo excitation zone, a fairly intense process of self-oscillations arose, preventing the normal operation of the engines.
3. When the engines were turned on, the booster made an active turn with noticeable angular acceleration, which led to the differences in pressure at the inlet to the pumps of the engines located on different sides of the booster. And this, in turn, influenced the speed of development of Pogo and first of all, the engines began to turn off where this speed was higher.
4. During the engines operation, due to an increase in longitudinal acceleration, the hydrostatic pressure of liquid oxygen increased, and, accordingly, the pressure at the inlet to the pumps. In addition, the control system soon brought it up to nominal, and in this operating mode the engines left the depths of "Pogo zone", ending up close to its border or even beyond it. The Pogo process either began to fade or stopped completely.
5. A decrease in the mass of the booster due to propellant exhaustion, which led to a slight increase in the own frequency of elastic oscillations of the booster, that is, slightly shifted the boundaries of "Pogo zone", or

simply random pressure fluctuations that periodically occur in the fuel system, brought out of the unstable state of equilibrium at least one of the working engines and returned it to "Pogo zone", resuscitating or starting this process again.

6. After the first engine shutdown, the thrust of the power plant and the acceleration of the stage decreased abruptly, the hydrostatic pressure of liquid oxygen in front of the pump also abruptly dropped, the pressure drop across it increased, and the hydroacoustic frequency, having decreased, moved deeper into "Pogo zone" again, accelerating self-oscillations. And with each subsequent engine shutdown, this process only accelerated like an avalanche.
7. The explosion and destruction of an object in which a fairly intense Pogo process has arisen and developed is its usual result. About how during Pogo, seemingly without visible preconditions, the engines instantly turned off, and then a powerful explosion occurred, after which the rocket structure shattered into small pieces, S. P. Korolev, as well as his successor V. P. Mishin in due time could tell something about this [11, 12].

It is advisable to consider a more complex process of self-oscillations development, taking into account the differences in the lengths of pipelines supplying liquid oxygen from the tank, for two groups of engines, only if accurate data on the design of the booster are available.

Other possible explanations for the explosion of B9 booster during boostback, which are not based on the analysis of emergence, development and/or attenuation of Pogo processes, but only on problems associated with a simple loss of propellant supply to the engines during strong changes in the parameters of the booster movement, are a priori disavowed by a fairly obvious consideration. SpaceX, of course, had to work out all engine operating modes during boostback on the stands. And with the care it demonstrates in debugging Raptor-2 engines, it's hard to doubt that it was all done. Therefore, we can assume that only the appearance of a factor that was not simulated on test stands, but that arises exclusively in flight, could lead to the fact that the explosions of both stages of Starship were so unexpected for the company that until January 12, 2023, 8 weeks after IFT-2, its leadership continued to remain silent about the causes of these incidents.

Conclusions

1. The strong influence of factors external to the power plant of Starship booster on the frequency of own hydroacoustic oscillations in the oxygen supply line, which determines the possibility or impossibility of Pogo-type longitudinal self-oscillations’ excitation, has been demonstrated.

2. It is also shown that the constructed numerical model of two-stage process with a variable frequency of hydroacoustic oscillations completely explains all 7 of its visible features that preceded the explosion of the booster during boostback.

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