Analysis of Starship third and fourth flights main results

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Gallant fellows, these soldiers; they always go for the thickest place in the fence.
Sir John de Robeck

Summary

This paper analyzes the main results of the fourth flight of Starship, and, based on newly obtained data, clarifies some aspects of the third flight of this rocket system. It is shown that in the fourth flight, the engine ignition program at the start caused again return of auto-oscillations of Pogo-type in the transient mode, which led to loss of one engine of the system. At the finish of the return maneuver (boostback) of first stage, as a result of too late shutdown of the inner ring engines, apparently due to Pogo, another engine was lost, causing a fire in the booster and its explosion after splashdown. The jettison of intermediate compartment led to a change in the operating modes of the booster engines during final braking and allowed it to be successfully completed even with one failed engine.

During the fourth flight, the second stage of the Starship system completely passed the stage of aerodynamic braking in the Earth's atmosphere, however, at the very finish, the right flap (or perhaps both flaps) of its forward tail detached due to the fact that at hypersonic flight speeds the bow shock wave hits the forward tail, which leads to separation of the boundary layer on it with a multiple increase in heat flow in the separation zone compared to any other place on the surface of the second stage. Thus, the used configuration of forward fin flaps is completely inadequate and must be changed.

Key words: *Pogo, self-oscillations, Starship, frequency, excitation, hydroacoustic oscillations, shock wave, thermal flux*

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

I. Introduction

The fourth test flight of Starship, which took place on June 6, 2024 [1], turned out to be the most successful in the entire test series: both of its stages made soft landings in ocean waters for the first time. However, this flight didn't go as smoothly as follows from the official reports of SpaceX [2]: apparently, booster exploded after landing, and Ship literally miraculously didn't lose stability due to the destruction of forward flap, which completely broke off at the very last moment before splashdown, which allowed Ship to reach the finish line [1]. In addition, at the very start, unlike the second and third launches, one of the booster engines immediately failed, and the rocket system at that moment experienced the strongest acceleration fluctuations, no matter how greater than at the onset of the development of Pogo-type self-oscillations during the second launch. And, finally, the data from the fourth flight made it possible to clarify the estimates associated with attempt to land the booster on water in the third flight [3].

In general, judging by the information received, contrary to expectations, the fight against Pogo oscillations in the fourth flight wasn't completely over, and the paper will first be devoted to the analysis of this aspect of IFT-4 flight. In addition, it will be necessary to consider the next critical threat to the Starship program – destruction of the forward flap of Ship (second stage). It was clearly to a qualified aerodynamicist in the field of hypersonic flows from the very beginning after the appearance of the first drawings of such configuration, but in SpaceX company, obviously, there have never been such and still are not. And now this problem has finally begun to manifest itself in reality and is now coming to the fore.

II. Demonstration of Starship trajectory main parameters in the third and fourth flights

In the source [4], shortly after the fourth flight, as previously after the three previous ones, main parameters of Starship were presented based on the data obtained from the video stream [1]. Fig. 1 shows the system data along the flight trajectory of the first stage (booster B11), and Fig. 2 – along the flight trajectory of the second stage (Ship S29) until the moment of engine shutdown during acceleration.

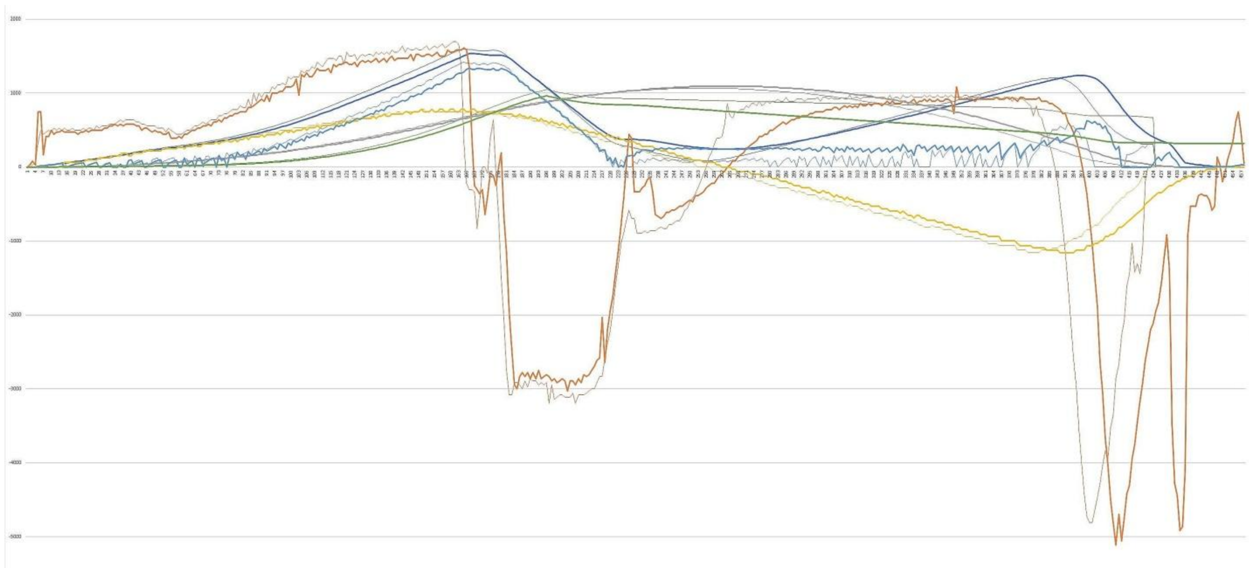

Fig. 1 – Acceleration, speed, altitude and direct (horizontal) range, as well as horizontal and vertical speed components of Starship booster in the third and forth flights [4]

In Fig. 1, 2, a comparison was also made in time (in seconds) of six parameters of Starship first and second stages in the third and forth 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 forth flight are displayed in thick lines, and data related to the third flight are displayed in thin lines. Acceleration is shown with purple-brown lines, speed with blue lines, and altitude and range with black lines.

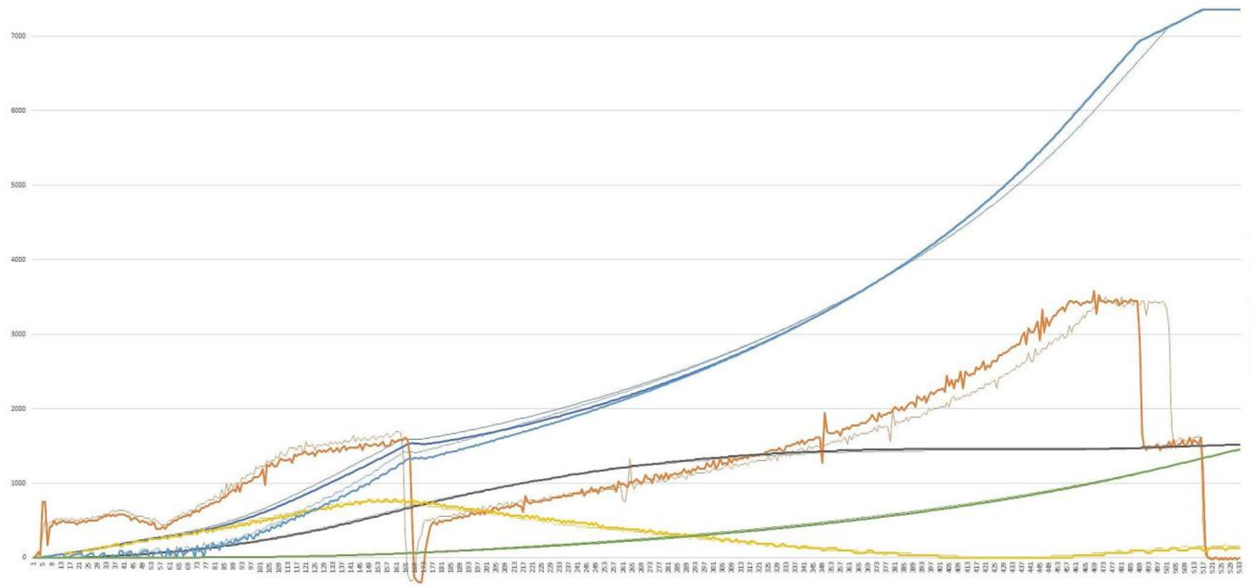

Fig. 2 – Acceleration, speed, altitude, direct range, as well as horizontal and vertical velocity components of Starship second stage in the third and forth flights, including as part of stack [4]

The accelerations shown here are inertial without taking into account the gravitational acceleration. It should also be understood that after separation and the return maneuver, the direction of the booster flight changed to the opposite, and the algorithm by which the acceleration is calculated doesn't take this into account, and therefore accelerations change sign, and after 170 – 180 seconds of flight, the negative accelerations in Fig. 1 are actually positive, that is, pressing the fuel components to the lower bottoms of the tanks, which creates conditions for its normal supply to the engines. And in the interval from about the 275th – 290th to ~ 380th second during the free flight of the booster, under the influence of almost only gravitational forces, the stage is in zero gravity and the total acceleration there is close to 0.

III. Analysis of Starship behavior in the third and fourth flights in the vicinity of first critical point of the fourth flight

The first critical point of the fourth flight, that is, the point in the rocket system trajectory where the first process of growing Pogo-type oscillations began, to some surprise of the author, was again the phase of the trajectory immediately after liftoff, approximately the same as in the second flight, when Starship architecture first began to include Intermediate interstage compartment. Then, as analyzed in paper [3], the process that began, when the engines go to their nominal operating mode, spontaneously died out. All engines continued to operate, but the oscillations of the rocket's longitudinal acceleration from approximately the 4th to the 19th second were quite large. In the third flight, the rate at which the power plant reached its nominal thrust mode was changed, and Pogo-type oscillations disappeared. However, in the fourth flight, as far as can be judged from the fairly approximate acceleration graphs we have, there was a return to the engine thrust control program as in the second flight, and sharp oscillations of the rocket's acceleration appeared again. Moreover, one outer ring engine immediately shut down, which didn’t happen in either the second or third flights.

Fig. 3 – Iconography of engine activation at takeoff for Starship last three flights

This is confirmed by the iconography that was shown in the video streams of all three flights under consideration. When Starship is launched, the inner 13 engines are first fired, then, after a second delay, the 15 engines of the outer ring, and then, after about another second, the remaining 5 outer engines, see the first 3 fragments at the top of Fig. 1 from the stream of the second launch. They show the moments in time when the iconography with corresponding quantity of operating engines first appears.

In the third flight, the iconography generally coincided with what happened in the second flight, but all engines were turned on a second later (see the fourth fragment of Fig. 3), and the rate of thrust buildup was initially noticeably behind the rate in the second flight, and then began to noticeably outpace it, and the auto-oscillations of Pogo didn’t have time to develop during this transient mode of engines operation. But in the fourth flight (see the fifth, lower fragment of Fig. 3), there was a return to approximately the previous engine control algorithm, and, judging by the available data, Pogo-process also returned, which led to the loss of one engine out of 33 at launch. Such inconsistency in the decisions of Starship creators is difficult to explain logically.

So, the work assessing the consequences of Starship explosion above the launch site [5] is again relevant.

Because there were fewer engines operating, Starship acceleration during first stage boost was slightly lower and its duration was 3 seconds longer, so the rocket system's speeds at stage separation differed slightly (see Fig. 1).

IV. Analysis of Starship behavior in the third and fourth flights during boostback

As shown in papers [6, 7], the next critical moment for Pogo in the second flight of Starship was the period during which its first stage performed an active maneuver to turn around and enter the return trajectory (boostback). Due to self-oscillations during this maneuver, the first stage (booster) engines didn’t start, turned off, and, ultimately, everything ended with the booster exploding [7]. In the next, third flight, after analyzing the results of the previous flight, the frequencies of hydroacoustic oscillations in the lines supplying oxygen to the booster engines and the frequencies of elastic vibrations of the structure were obviously determined, after which, in accordance with the algorithm presented in [6, 8], the operating modes of the power plant during the boostback were changed in order to "spread" the frequencies of these oscillations. After this, the booster performed a boostback without exploding, and based on the data available at that time, there was concluded in paper [7] that Pogo-type oscillations during the boostback was suppressed. However, one and a half months after the third flight, SpaceX announced that during IFT-3, during the boostback: "All 13 engines ran successfully until six engines began shutting down, triggering a benign early boostback shutdown" [9]. As a result, the booster's return flight trajectory was steeper than planned, and it exploded during its final braking over the ocean, ~30 km further from the shore than planned.

All this can be explained by the fact that the estimates of the possible moment of Pogo onset during boostback, based on the approximate formula for recalculating the effect of engine operating modes on the frequency of hydroacoustic oscillations, turned out to be slightly inaccurate, and on some engines at the very end of the maneuver, self-oscillations of Pogo still began. SpaceX should have used more accurate results of direct calculations of hydroacoustic oscillations, which aren’t yet available to them. However, SpaceX, as far as we can judge, is doing everything to ensure that this state remains for them forever. The second option for explaining the failure of 6 engines is that SpaceX didn’t sufficiently take into account the increase in the frequency of elastic oscillations of the booster structure due to a decrease of its mass because of fuel consumption during boostback. One way or another, 6 engines out of 13 turned off or were permanently turned off, and the final braking maneuver of B10 booster over the ocean surface in the third flight was a complete failure.

However, if you look at Fig. 1 and compare acceleration graphs for the third and fourth flights during the boostback, you can see that both the maximum acceleration values and the engine operating time in this mode are almost identical, and it is very difficult to understand from this that 6 engines shut down prematurely during IFT-3. And masses of the boosters during the boostback in both flights should have been approximately the same, since the intermediate compartment weighing about 9 tons was dropped during IFT-4 2 seconds after the engines stopped working. So the thrust of the power plant during the fourth flight, if it was less, was very insignificant, and to fully resolve the issue of the possibility of Pogo inducing at the very end of the boostback during IFT-3, more complete and accurate data are needed than those in the public domain. It also becomes clear that the information in the SpaceX release about the final part of IFT-3, as usual, doesn’t quite correspond to reality.

But, from a comparison of the graphs in Fig. 1 and the iconography of the video streams, it is quite possible to conclude that during the IFT-4 boostback, SpaceX followed the path already tested during IFT-3 on the second stage of the rocket system: if the boundary of Pogo excitation zone is reached by the rocket system shortly before the end of the next phase of power plant operation, then at this moment the control system turns off those engines whose characteristics have approached Pogo zone, and the final impulse is realized by the remaining part of the engines, which have a different length of the fuel component supply lines, and which, therefore, are quite capable of continuing to operate without exciting self-oscillations. This has already been done twice at the finish of the second stage acceleration, when 3 more efficient Raptor-2 engines with a vacuum nozzle were turned off approximately 15 seconds before the end of the stage acceleration during IFT-3 and 28 (!) seconds during IFT-4, and only 3 central engines with conventional nozzles continued to operate, see Fig. 2. During the boostback at IFT-4, all 10 engines of the inner ring of the booster were switched off in advance and in an organized manner (symmetrically in two groups of 5 engines) over a fraction of a second, and its final acceleration towards the launch site over 8 seconds was carried out only with the help of 3 central engines [1]. While at IFT-3, the engines were randomly switched off over the same 8 seconds. The last to switch off were 3 central engines, but their delay compared to the last engine of the inner ring was only about 1 second [10]. Moreover, their shutdown occurred asymmetrically, which deflected the booster's flight speed vector and put it on an unplanned, steeper and shorter return trajectory with the point of impact twice as far from the launch site as planned.

It should also not be forgotten that during the final braking of the booster during IFT-4, 1 engine didn’t turn on. This could well have been a consequence of the fact that during boostback in fourth flight, at the end of the operation of the central ring engines, Pogo-process still began to be excited and disabled 1 engine instead of 6 in the previous flight, but then stopped due to their shutdown. Moreover, this was an engine from the second five to be switched off, which worked a little longer than the first. So, it should be necessary to switch off the inner ring engines a little earlier, and, it seems, both the launch and the boostback in Starship fourth flight were on the verge of a foul. If something had gone slightly wrong, we could have again witnessed either the already quite familiar explosion of the booster in flight, or even a much more grandiose phenomenon – explosion of the entire Starship system at launch (see [5]).

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

Let us now return to the consideration of the first critical point of Starship third flight, related to the landing of the booster on the ocean surface [11]. The final braking with the engines during this maneuver occurred literally at the last kilometer of altitude and in this range of values was shown on the screen during the video demonstration [1] extremely inaccurately. Therefore the determination of the altitude of the start of braking during IFT-3, necessary for assessing the operating mode of the engines of the maneuver that hadn't yet taken place, was also very approximate. It was assumed that the final vertical braking maneuver began at an altitude of h = 1.0 km and a flight speed of v = 0.37 km/s. In this case, the inertial acceleration required for its implementation should have been about $w \approx 70$ m/s^2. Taking into account the gravitational acceleration, the total acceleration value would have been ~ 80 m/s^2 [3].

The required engine thrust and operating mode were estimated from this braking value – the throttling ratio of the 13 Raptor-2 engines at sea level in this case should have been about 0.63 of their nominal values [3]. Then the pressure ratio on the oxygen pump would have been about $p_2/p_1 \approx 110$, and the length of the liquid oxygen lines from the landing tank to Raptor-2 engine pump, provided that self-oscillations occurred, was estimated to be about 6 m. In this case, when estimating the frequency of elastic oscillations of the booster structure at about $f_e \approx 26.2$ Hz, it was possible to excite Pogo-type self-oscillations, since hydroacoustic oscillations would have occurred with a multiplicity of 3 in relation to elastic oscillations, see [3]. A similar set of characteristics would have described Pogo excitation that caused engine failures and the final explosion of B10 booster in the third flight.

The completion of the B11 booster's fourth flight was significantly more successful – it made a soft landing on the water surface at the calculated point in the Gulf of Mexico. As a result, it became possible to directly obtain the values of the booster's maximum acceleration during landing, get rid of errors caused by an unreasonably rough representation of the altitude in the iconography at its low values, and more accurately recalculate the characteristics of the power plant during the final braking of B10 booster.

From Fig. 1 it follows that the maximum inertial acceleration of B11 booster during landing was about 50 m/s^2. Its mass at this time should have been 9 tons less than that of B10 booster, due to the fact that during IFT-4 the intermediate compartment was jettisoned by this time. In addition, it was determined from the video that the fall speed of B11 booster by the time the engines were turned on was approximately 330 m/s, and that of B10 booster was 370 m/s. Therefore, during IFT-3 the inertial acceleration should have been about 56 m/s^2, and the total, taking into account the gravitational acceleration, about 66 m/s^2, but not 80 m/s^2 as in the first estimates presented in [3]. Then the thrust of the power plant should have been 15.2 MN, and the throttling ratio of these engines for thrust in this mode should have been about 0.52. And taking into account that the thrust falls somewhat faster than the pressure in the main combustion chamber of the engine decreases, we will consider the degree of throttling by pressure to be equal to ~ 0.55. Then the ratio of pressure on the oxygen pump will be $p_2/p_1 \approx 92.5$.

From the estimates of work [3] it follows that Pogo oscillations during the landing of B10 booster should have been excited at a frequency of hydroacoustic oscillations in the vicinity of $f_n \approx 8.7$ Hz. For this, with a ratio of pressure on the oxygen pump $p_2/p_1 = 92.5$, the length of the oxygen lines from the landing tank to the inner ring engines should be 6 – 7 m (see Table 1), which is on average approximately 1 m longer than the earlier estimates, and for the two extreme options the difference is almost absent [3]. So such lengths of the oxygen supply lines to the engines may well correspond to reality and cause the excitation of Pogo during IFT-3.

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	92.5	0.45	6.20	6.65	25.9	**8.99**
			6.60	7.05	26.7	**8.70**
			7.00	7.45	27.6	**8.43**

The following notations are used in tables: 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 equivalent 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.

Now let us analyze what changed during the fourth flight and why B11 booster, unlike B10 booster, didn't explode during the final braking. As is known, during the last flight after the boostback, an intermediate compartment weighing about 9 tons was jettisoned. This decrease in the booster mass by 4 – 5 % led to its more intense braking in the atmosphere and reduced the fall speed at the moment of engine activation from about 370 m/s to 330 m/s, i.e. by more than 10 %, and to a corresponding decrease in the maximum acceleration to 50 m/s^2. Together with the decrease in mass, this led to a decrease in the required engine thrust to 13.2 MN and a pressure drop on the oxygen pump to $p_2/p_1 \approx 80$, i.e. by 15 %. This causes a corresponding increase in the frequency of hydroacoustic oscillations by 7.5 %, and their removal from Pogo zone, that is, by difference more than ~ 8.5 % of the nominal excitation frequency of this process (see Table 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	80	0.45	6.20	6.65	24.1	9.63
			6.60	7.05	25.0	9.32
			7.00	7.45	25.7	**9.03**

Formally, the excitation of Pogo at the maximum calculated length of the oxygen lines is still possible, but it is necessary to understand that all these estimates, due to the lack of any precise data, have a qualitative rather than quantitative value, but, as follows from the entire array of works written on this topic, they allow us to understand what happened in all the test flights of Starship conducted to date.

It should also be remembered that the jettison of the intermediate compartment will also somewhat change the frequency of the own elastic oscillations of the booster hull, but calculation of these changes is beyond the simple methods used here to estimate such frequencies.

As a result of the previous analysis, it becomes clear why SpaceX began to jettison the intermediate compartment on the fourth flight after it had been installed on Starship after the first flight – otherwise, the booster would explode during landing due to the occurrence of another self-oscillating process of Pogo-type. But, frankly speaking, all these manipulations with the intermediate compartment are already starting to make me smile. Has no one at SpaceX realized yet that everything could have been done much more simply without any jettisoning of this compartment?

To do this, it was sufficient to remove 5 engines of the inner ring from Pogo zone during final braking, when saving the total thrust of the power plant, but increasing their thrust, and not to introduce the other 5 into this zone, reducing their thrust by the corresponding amount (the 3 central engines operate quite stably in this mode). Such option is shown in Table 3.

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 Super Heavy Raptor-2	75	0.45	6.60	7.05	24.2	9.60
	92.5				26.7	**8.70**
	110				29.0	8.01

As can be seen from it, the departure of the engines from a throttle level of ~ 0.55 (middle line) to throttle levels of ~ 0.45 and ~ 0.65 reliably takes their operation out of Pogo zone, if they were there before, with practically no change in their total thrust.

However, the adventures of B11 booster on its fourth flight not finished there. During the final braking, one of the inner ring engines, apparently damaged at the very end of the boostback, didn't turn on, and a powerful fire can be seen in the video of the booster landing on the water [11], see Fig. 4.

Fig. 4 – Fire on B11 booster before splashdown

Most likely, this fire was caused by the destruction of fuel lines of the very same engine that didn’t turn on. Video [11] doesn’t show the end of the booster landing on the water, SpaceX's message about the fourth flight [2] doesn’t say anything specific about what happened to the booster after splashdown, and no one else has seen B11 booster anywhere. Therefore, it either sank quickly or exploded. From the totality of data (fire, silence from SpaceX), the most likely option is the booster explosion after landing, much like the explosion of SN 10 prototype on March 4, 2021 during testing [12].

VI. Shock waves and heat flows at hypersonic flight speeds

Nevertheless, it can be considered that for the current version of Starship, most of the problems associated with the excitation of auto-oscillations of Pogo-type have been more or less resolved over the past 4 test flights. When switching to a new version of the system, they will arise again, but for now, issues related to the braking of the second stage when entering the Earth's atmosphere at orbital speed come to the fore. This is a fairly specific area of aerospace technology, and, as a rule, an outside observer can't appreciate their implementation in any way. However, in some cases, exceptions are possible, and the Starship program is one of such exceptions.

This section of the paper will discuss the problem of the emergence on the surface of bodies of complex geometry, streamlined by a hypersonic gas flow, of narrow zones in which heat flows are many times greater than what occurs even in the most heat-stressed points of simpler configurations. This effect was experimentally discovered and studied quite thoroughly several decades ago. It became clear that in places where shock waves fall on a solid surface, due to very strong pressure gradients generated by the shock, separation of the boundary layer flowing along this surface occurs. In the separation zones, very complex small-scale flows arise that cause heat flows exceeding those on these same bodies at the stagnation points (where, nominally, the heat flow is maximum) by 5 – 6 to 30 (!) times. The latter occurs during complex interactions of shock waves falling from the outside with shocks created by the body itself, on which the described effect is realized.

On cylindrical bodies with a conical or ogive nose section, at supersonic flight speeds, a bow shock is always formed, which at hypersonic speeds passes very close to the surface of such a body. At large angles of attack of the order of 40 – 50 degrees, typical for orbital aircraft braking in the atmosphere, the flow pattern, of course, becomes more complicated, but in the vicinity of the lower part of the vehicle surface, little changes qualitatively, and at the top there is a zone of relatively low pressures and densities, gas and comparatively low heat flows, which is called the "aerodynamic shadow" zone. In the middle section, the flow pattern is quite close to what takes place below the body.

From the above it should be clear that if the body has wing surfaces in the area of its nose in the middle diametrical plane, then the bow shock will fall on them, creating narrow zones of abnormally large heat flows, and it is fundamentally impossible to protect them from overheating. If these surfaces are transferred upward into the aerodynamic shadow, then the part that is inside the bow shock will create small aerodynamic forces and moments, and the part of the surface that protrudes from behind it will be cut off by it. Such configurations are fundamentally unviable at high hypersonic speeds.

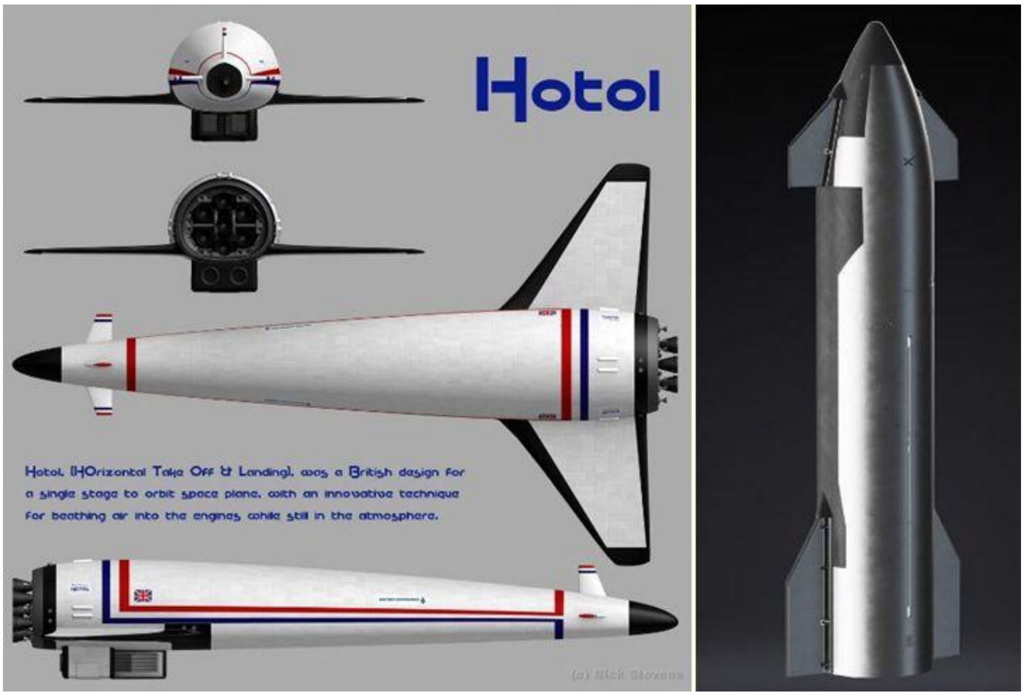

Fig. 5 – Hotol reusable orbital aircraft project (left) and Starship second stage (right)

Fig. 5 shows an image of the British Hotol single-stage-to-orbit aerospace plane with a combined air-breathing and rocket engine (developed in 1982–1991) [13] and Starship second stage [14] (the most early version of Hotol is shown here). What is important to us is that the configurations of the objects under consideration are qualitatively similar: both have canards for balancing and tail wing surfaces: Hotol has a wing for horizontal landing, and the second stage (Ship) has a tail for balancing. Hotol was never built, but the project developed for 9 years, and it is quite indicative of what its final aerodynamic configuration ended up being. Ship returned from orbit for the first time on June 6, 2024, and it is easy to see that the conclusion from the analysis of these two completely different programs on the issue of interest to us now is quite obvious.

In Fig. 6 we see a picture of the flow around surface fragment of the second stage (Ship) in the vicinity of the junction of the right forward flap with the body [1]. The straight line closest to the observer is the trailing edge of the flap. Flight altitude is 73 km, speed is approximately 7.3 km/s, Mach number is about 21.5. The heating of the surface as a whole is not very high yet, the maximum heat fluxes will be reached at an altitude on 3 km lower [15]. The upper surfaces of the vehicle are dark and still relatively weakly heated, but not far from the base of flap tail edge we see a very bright area – this is the boundary layer separation zone created by bow shock, which generates a narrow area with heat fluxes that are many times greater than those in any other place of the vehicle, with the exception of a similar zone located on the left forward flap.

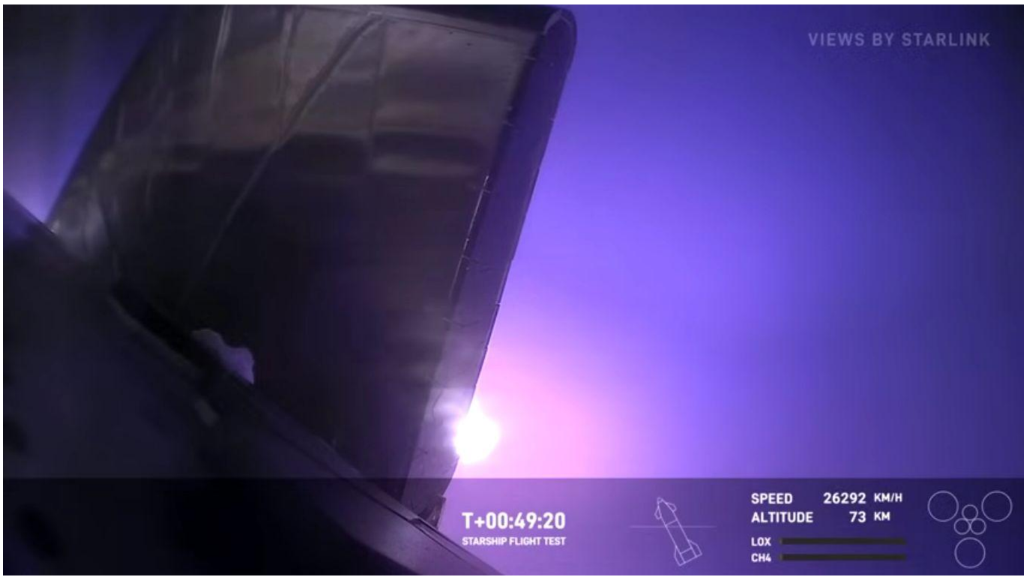

Fig. 6 – Picture of hypersonic flow around the junction of hull with forward flap at the beginning of braking in the atmosphere

Fig. 7 – Picture of hypersonic flow around the junction of hull with forward flap in the middle of braking

Fig. 7 shows the same fragment of Ship surface after 9 minutes. Flight altitude is 54 km, speed is about 4.1 km/s, Mach number is about 13. The rear part of the flap in the place we are describing is already partially destroyed, and as the video shows [1] small pieces of material continued to fly off from it. In the end, it will fall off in this place, but fortunately at the moment when there was no longer any need for it [16]. It is unknown when the left flap fell off, since no TV camera was aimed at it, but most likely at about the same time.

Thus, it is absolutely clear that such geometry of the second stage is absolutely inadequate, and the vehicle with such forward tail will never fly normally. The developers of Hotol system gradually came to the same conclusions. Fig. 8 shows (looking from top to bottom) how during 1985 the forward horizontal flaps disappeared. It was replaced by extensions in front of the wing. The vertical tail remained in 1985, but due to the fact that it was in the aerodynamic shadow zone, it grew in size [17].

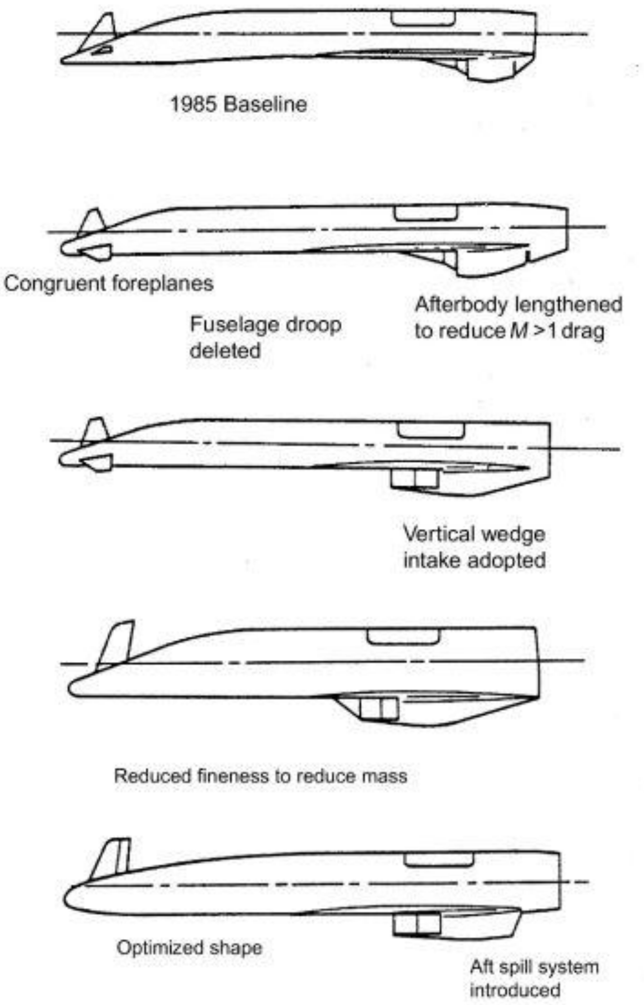

Fig. 8 – Transformation of aerodynamic configuration of Hotol orbital aircraft during 1985

But, in the end, it had to be removed back, clearing the nose from any wing surfaces [17], see also Fig. 9 [18]. Since it is obvious that SpaceX didn’t have and doesn’t have qualified aerodynamicists in the field of hypersonic speeds, it will probably they come to something similar after many test flights and a lot of time. And only then will regular, rather than test, flights of reusable Starship become possible.

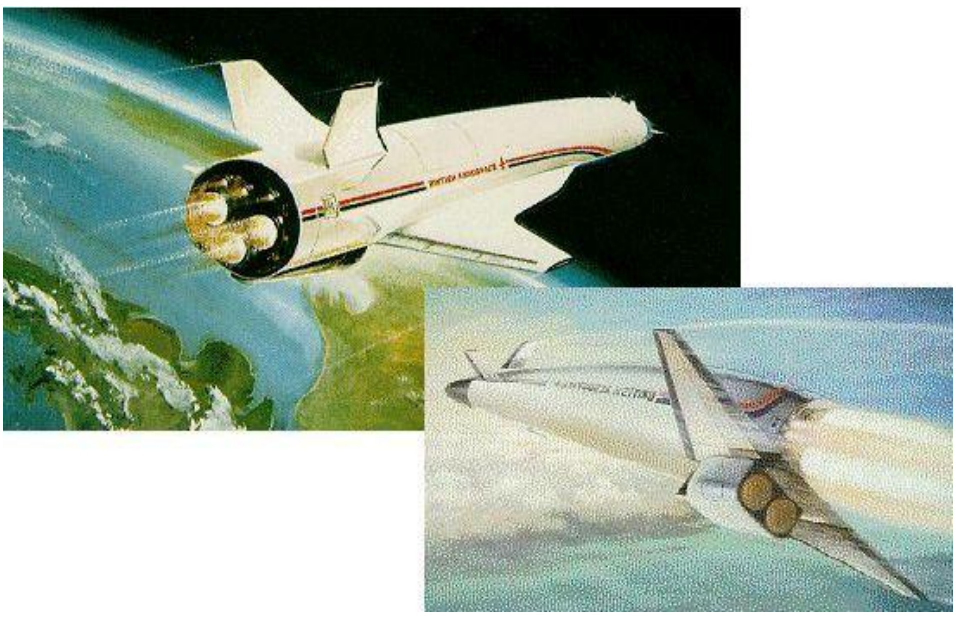

Fig. 9 – Initial (bottom) and final (top) layouts of Hotol orbital aircraft

Conclusions

1. During the fourth launch, the mode of reaching the nominal thrust of B11 booster's engines was returned to approximately the same scenario as during the second launch, which, unlike the third launch, again led to the excitation of Pogo-type self-oscillations at the start, which died down when the power plant reached the nominal operating mode, but caused one of the engines to shut down.

2. At the end of the return maneuver (boostback) of B11 booster, to prevent the occurrence of Pogo in this flight mode, only the 3 central engines were working, however, judging by the available data, one of the inner ring engines was not turned off before it was damaged as a result of the occurrence of self-oscillations.

3. On the fourth flight, B11 booster avoided an explosion during final braking and made a soft landing on the ocean surface because of jettisoning of the intermediate compartment, the booster engines were operating at lower thrust than those of B10 booster, but due to an engine fire, apparently damaged during the final boostback, B11 most likely exploded after splashdown.

4. During the fourth flight, the second stage S29 completely passed phase of aerodynamic braking in the Earth's atmosphere, however, at the very finish, the right forward flap (or perhaps both forward flaps) came off.

5. This was a natural consequence of the fact that the forward flaps are hit by a bow shock wave at hypersonic speeds, which leads to separation of boundary layer on them with a multiple increase in heat flows in the separation zone compared to any other place on the surface of the second stage, including the braking point on its nose and on the leading edges of forward and tail flaps.

6. Therefore, the used configuration of the forward flaps is completely inadequate and must be changed, what is more shifting it upward into the aerodynamic shadow zone will not lead to any significant results.

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Moscow,
24.06.2024

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