Variations of Solid Rocket Motor Preliminary Design for Small TSTO launcher

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Abstract

Several combinations of solid rocket motors and ignition strategies have been considered for a small Two Stage to Orbit (TSTO) launch vehicle based on a big solid rocket motor first stage and cryogenic upper stage propelled by the Vinci engine. In order to reach the target payload performance of about 1400 kg into GTO for the clean version and 2700 to 3000 kg for the boosted version, the influence of the selected solid rocket motors on the upper stage structure has been studied. Preliminary structural designs have been performed and the thrust histories of the solid rocket motor have been tweaked to limit the upper stage structural mass. First stage and booster combinations with acceptable general loads are proposed.

Nomenclature

Isp	specific impulse	s
g	gravity acceleration	m/s²
m	mass	kg
m_dot	propellant mass flow rate	kg/s
q	dynamic pressure	kPa
v	velocity	m/s
α	angle of attack	°
γ	flight path angle	°

Subscripts, Abbreviations

AP	Ammonium Perchlorate
GLO mass	Gross Lift-off mass
GTO	Geostationary Transfer Orbit
HTPB	Hydroxyl Terminated Poly-Butadiene
HTPB 1912	HTPB with 69% NH_4ClO_4, 12% HTPB, 19% Al
ISS	International Space Station
LEO	Low Earth Orbit
MEO	Medium Earth Orbit
MEOP	Maximum Expected Operating Pressure
MR	Mixture Ratio
MTO	Medium Transfer Orbit
NGL	New/Next Generation Launcher
SI	Structural Index (m_{dry} / $m_{propellant}$)
SRM	Solid Rocket Motor
TSTO	Two Stage To Orbit
US	Upper Stage
VENUS	Vega New Upper Stage
avg	average during the flight
s.l.	sea level
vac	vacuum
2 + 2 P23	4 P23: two ignited on ground and two with a delayed ignition

1. Introduction

Solid rocket motors (SRM) are commonly used for boosters or launcher first stage. Indeed they can provide high thrust levels while being compact, light and relatively simple compared to a liquid rocket engine providing the same thrust level. However their thrust history cannot be chosen as wished. The geometrical design of the grain and the choice of the propellant offer some flexibility; nevertheless not every thrust history is feasible.

During the preliminary design of a launcher, it can be noted that the choice of a given thrust history for a solid rocket booster or first stage has a significant influence on the launch vehicle performance and consequently on the whole staging. Indeed during the ascent, the gravitational losses play an important role. They can only be reduced by a rapid ascent, which requires high thrust levels. But some limitations have to be taken into account. The maximum acceleration should usually not exceed 4.5 to 5 g in order to provide an acceptable environment for the payload. The maximum dynamic pressure should also be kept under a certain level in order to facilitate the controllability of the launcher and also to keep the mass of the fairing low. The maximum acceleration and dynamic pressure also influence directly the mass of the upper stages. Taking these limitations into account, a thrust history maximizing the performance can be determined.

Since 2007 [1], DLR's group for Space Launcher Systems Analysis (SART) is studying a promising concept based on technologies already existing and aiming at exploiting synergies with other European programs. This concept is a Two-Stage To Orbit (TSTO) launch vehicle based on a solid rocket motor for the first stage, using the same technologies as the P80 FW of Vega, and a large cryogenic (LOx/LH2) upper stage propelled by the 180 kN Vinci expander cycle engine with its deployable nozzle. It is expected that this technological choice would lead to a reduction of development and production costs and an increase of the quality of production. Vega and the next European heavy lift launcher (each of the options in discussion nowadays (Ariane 5 ME or NGL/Ariane 6) are supposed to use Vinci) would also benefit for at least one of their stages from this concept.

The goal of this small TSTO launcher is to fill the performance gap between Vega and Soyuz by making possible, for instance, Galileo satellite replacement single launch missions. Moreover small scientific satellites launched towards the Moon, asteroid or other planets could also benefit from such a launcher. In a longer term the performance could be increased with additional strap-on boosters to replace, if needed, Soyuz for launch from Kourou. In this case a payload performance between 2700 kg and 3000 kg in GTO would be needed [2].

The first preliminary versions of this concept were studied in the frame of the VENUS (VEga New Upper Stage) study. Although the main goal of this DLR-EADS Astrium joint effort funded by the DLR space agency focused mainly on 3-stage and 4-stage configurations [3], a 2-stage configuration (denoted "F") was also studied. A preliminary analysis showed that replacing the current Vega Z23 solid 2nd stage, Vega Z9A solid 3rd stage and the AVUM 4th stage with a big cryogenic upper stage would bring a significant increase of performances compared with Vega. Indeed a P80 FW-H18 (cryogenic upper stage with 18 tons of LOx/LH2) would be able to put up to 2675 kg into the reference orbit of Vega Launch vehicle (700 km, polar and circular) [1]. Using a P100 solid rocket motor (solid rocket motor with 100 tons of propellant), replacing the P80 FW of Vega associated with a H17 cryogenic upper stage propelled by Vinci increases the performance over 3000 kg in the reference orbit of Vega. A preliminary assessment of the performances of this launch vehicle for other missions results in a payload performance of almost 1000 kg to MTO (250 km x 23216 km, 56°) and slightly less than 950 kg to GTO (250 km x 35943, 5.4°) [4]. In both cases it is however insufficient to launch a Galileo replacement satellite equipped with the propulsion system required for the transfer from MTO to MEO. Consequently this study was continued with the investigation of TSTO launch vehicles equipped with bigger first stage solid rocket motors, which can be manufactured with no or small modifications of the current facility of Kourou.

2. Scope

The diameter of the solid rocket motors produced in Kourou: Ariane 5 EAP (Etage d'accéleration à poudre) and Vega first stage P80 FW is 3 m. The first iterations of the preliminary design took into account this diameter for the whole launcher and showed that a P160-H26 could achieve a payload performance of almost 1500 kg into a GTO. A boosted version has also been considered. Thanks to two P30 strap-on boosters the payload performance of this launcher can be increased, according to preliminary estimations, to up to almost 2800 kg in GTO. [5] This results correspond to the targeted performance range, however the final configuration was deemed to have an excessively high aspect ratio, which would potentially have a negative impact on the controllability of the launcher. This has not been studied in this preliminary design until now.

For this reason the latest analysis took into account an increase of the launcher diameter from 3 m to 3.5 m. This has for main effect to reduce the aspect ratio and ease the grain design of the first stage. In addition this modification is expected to have a positive effect on the reduction of the pressure oscillation in the first stage.

The main focus of the results presented below are the reachable performances of launcher with a diameter of 3.5 m and first stages with a propellant loading situated between 160 and 170 tons. All these motors have monolithic casing based on the technologies of Vega's P80 FW first stage. In order to increase the performance, different solid propellant strap-on boosters with propellant mass in the 20-45 tons range are also considered. The influence of the thrust law of these solid rocket motors on the whole launcher design and staging is studied thanks to an assessment of their effect on the structural mass and on the corresponding optimum trajectory.

3. Definition of the launch vehicle

As stated previously, the launch vehicle considered here are TSTO launchers. Indeed it appears to be the simplest and most cost effective option for a new launcher, when considering the technologies available in Europe. The first stage is derived from the P80 FW used on Vega in order to take advantage of the experience gathered during its development.

For the upper stage, the high performances Vinci engine, equipped with its deployable nozzle is chosen. Its thrust level plays an important role. But no thrust level optimisation has been done for the upper stage. In fact, according to previous studies [6] and [7], a thrust higher than 180 kN would be beneficial for the staging. The Vinci engine is nowadays the most powerful upper stage engine available in Europe. Due to the chosen thermodynamic cycle, the expander cycle, any increase in thrust level would be challenging and would require several important and expensive modifications and/or redesigns of the Vinci rocket engine.

Concerning the strap-on boosters, two main different approaches have been followed. In the first one, two solid boosters are added and ignited at lift-off. The second option is based on four boosters. Two of them are ignited on ground and are jettisoned directly after burnout. The second pair is ignited once the first one has been jettisoned and is kept attached to the first stage. In this second option the four boosters are strictly identical, to reduce the development and production costs. The expected advantage of a configuration with delayed booster ignition is to be able to reduce the loads such as the maximum dynamic pressure and the maximum product of dynamic pressure and the angle of attack. Indeed the resulting thrust surplus cannot be reached, due to grain geometrical limitations, with a unique pair of booster ignited at lift-off.

A sum up of the characteristics of the launcher is presented in Table 1.

Table 1: Main characteristics of the TSTO launch vehicle

Characteristic	Value
Launcher diameter [m]	3 – 3.5
1st stage propellant loading [tons]	120 - 170
1st stage propellant	HTPB1912
1st stage Isp s.l. [s]	242.1 (avg[1])
1st stage Isp vac [s]	277 (avg[1])
US propellant loading [tons]	23-29
US engine	Vinci
Vinci Isp vac [s]	464
Vinci m_dot [kg/s]	39.5
Vinci MR [-]	5.8
Vinci Mass [kg]	589
Booster propellant loading [tons]	20-45
Booster Isp s.l. [s]	245 (avg)
Booster Isp vac [s]	275 (avg)
Booster number	0, 2 or 4

The pre-design of the different launchers has been done with the help of DLR-SART software for the design of the feed system of the upper stage, for the estimation of the masses of the structure and the different subsystems for the determination of the aerodynamic characteristics and for the optimisation of the trajectories. The selected reference trajectory is the GTO (250 km x 35943 km, 5.4°) and corresponds to launches from Kourou in French Guiana. Only performances for this orbit are given. The performances in MTO, for example for the injection of a Galileo satellite, are slightly higher. All performances given in this paper take into account a deorbit boost to allow the re-entry of the upper stage just after the end of this mission. This is done thanks to a small solid rocket motor. More details about the de-orbit strategy are given in [5]. In the following chapters, the characteristics considered for the structure and/or the thrust law of the first stage, the boosters and the upper stage will be presented.

4. Preliminary sizing of the first stage

4.1. Structure

All first stages considered in this study take advantage of the carbon–epoxy filament wound monolithic motor case technology developed for P80FW SRM used on Vega. This choice is motivated by cost and simplicity reasons. In addition the diameter is kept between 3 m and 3.5 m in order to be able to use the Guiana Propellant Plant in Kourou such as the casting pit with no or few modifications (diameter up to 3.7 m are possible).

Therefore the characteristics of the first stage of the TSTO launch vehicle are very close to those of P80 FW. The maximum pressure in the combustion chamber is not exceeding 90 bars. According to the data available on the first stage of Vega [8], the structural index of the P80 FW SRM, defined as the dry mass divided by the total propellant mass is about 8.4%. It can be noted that even the Z23 second stage and Z9A third stage used on Vega have similar (even slightly better) structural index for a smaller propellant mass and a slightly higher maximum

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[1] The given specific impulse is the average value for the entire burn time including the lower thrust phase at the end of the burn time.

combustion chamber pressure. As a consequence it has been decided to select a structural index of 9% for each different first stages considered. Indeed contrary to P80FW, strap-on boosters should be attached to the first stage and its structure should be reinforced. In addition 10% system margins are added to the mass.

4.2. Thrust law

In total 12 different SRM with propellant loadings varying between 120 tons and 170 tons, have been predesigned since the beginning of this study. Some thrust profiles have been chosen to limit the gravity losses thanks to relatively high thrust levels. The others have been designed to limit loads such as the maximum dynamic pressure, the maximum acceleration, or the maximum qα (product of the dynamic pressure and the angle of attack).

The design philosophy of the thrust history is shown in Figure 1.

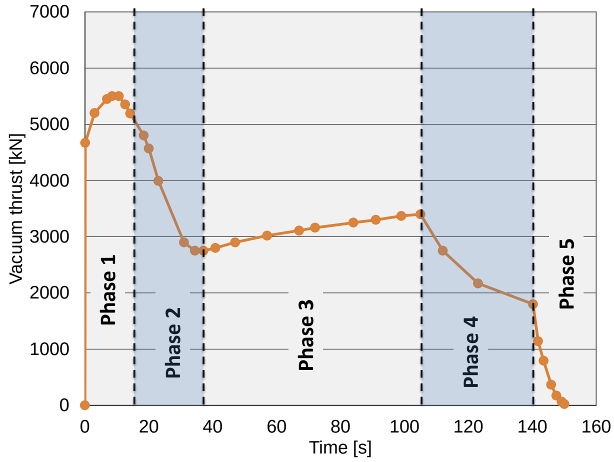

Figure 1: Design philosophy of the thrust history

Five phases can be distinguished. During the phase one, it is important to reach rapidly a high thrust level in order to allow the launch vehicle to lift-off and reach a high velocity: the higher the velocity the lower the gravity losses. It should be noted that during this phase the aerodynamic losses are still small compared to the gravity losses. While the rocket is accelerating the dynamic pressure keeps increasing. In order to avoid reaching a too high maximum dynamic pressure (which would require a strong and thus heavy structure and might also complicate the controllability of the launcher) the thrust level reduces sharply in a second phase. Just after passing the maximum dynamic pressure, the thrust can increase again. Often the increase in thrust level is limited by possible SRM grain geometries. The third phase ends when the maximum tolerated acceleration is reached. During the phase four, the thrust level has to decrease in order to follow the reduction of the launcher mass and avoid that the acceleration exceed the levels previously reached. The last phase, phase five, corresponds to the sharp drop-off of the pressure in the combustion chamber and the corresponding reduction in burn rate. In some cases the separation of the first stage can be done early during this phase. However this option was not considered in this study. Indeed the upper stage cannot be ignited immediately after the separation of the first stage to move away from the latest, which still has a residual thrust. After the separation, some time is needed for the deployment of the nozzle of the Vinci engine and the engine chill-down, prior to ignition.

The thrust histories of the P120, P140 and P150 SRMs have been optimized for the unboosted version of the TSTO launch vehicle. This was not the case for the P160 and the P170 SRMs. As a matter of fact, the boosted version has been used for the optimization of their thrust levels. For this reason most P160 and P170 SRMs have a maximum thrust level in the same range as those of the P150 SRMs. They also have a relatively longer burn time. The goal was to avoid reaching too high dynamic pressure and/or acceleration levels for the boosted version and simplify the design of the booster thrust law. It was not allowed for the boosters to have a longer burn time than the first stage. The only exception to this moderate thrust level is the P170 type 4 SRM which has a quite short burn time and, comparatively to the other SRMs, a very high maximum thrust. Its thrust history was designed to study the impact of such a high thrust on the increase of the required structure mass and the reduction of the gravity losses. The thrust histories of the different SRMs considered in this study are plotted in the Figure 2, Figure 3 and Figure 4.

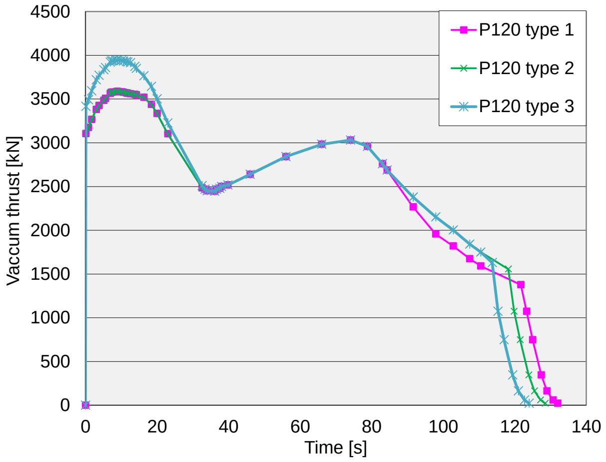

Figure 2: Vacuum thrust history of P120 SRMs

As stated in chapter 4.1, the maximum combustion pressure allowed has been set to 90 bars. As for P80 FW, Z23 and Z9A, the HTPB1912 propellant has been selected with a finocyl type grain shape. A non-yet optimized nozzle expansion ratio of 16 has been selected. Computations have been done to determine grain geometries approaching the desired thrust laws and to confirm the chosen first stage diameter.

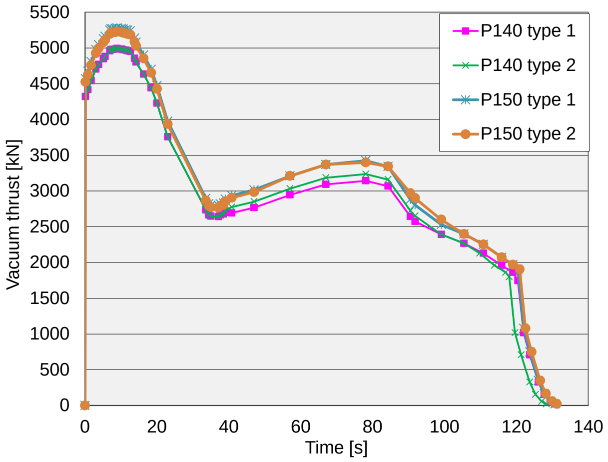

Figure 3: Vacuum thrust history of P140 and P150 SRMs

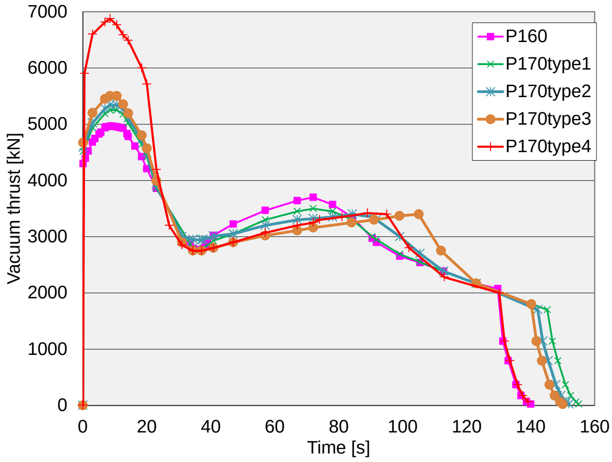

Figure 4: Vacuum thrust history of P160 and P170 SRMs

5. Preliminary sizing of the boosters

5.1. *Structure*

As for the first stage, the boosters pre-designed for this study are based on the carbon-epoxy filament wound monolithic motor case technology developed for the SRMs of Vega. The diameter of these boosters is varying between 1.52 m and 2.2 m, depending on the total propellant loading and the thrust history. No structural computation has been performed to determine the mass of the casing. The selection of the structural index has been done based on the one of Z23. Indeed the second stage of the Vega launch vehicle is the European SRM which is the closest in term of propellant mass and combustion pressure to the boosters that are considered in this preliminary design. According to the published data the structural index is a bit lower than 8% for a diameter of 1.9 m and a maximum combustion pressure of 95 bar [8]. This SRM is however not designed to be a strap-on booster. On the contrary, the GEM-60 SRM manufactured by ATK for the Delta IV M+ launch vehicle, was designed from the beginning to be a strap-on booster. Despite a moderate maximal combustion chamber pressure of 56 bars, the structural index is 13.6% [9]. This can probably be explained by the technology used to manufacture the casing and the relatively high aspect ratio of this booster which has a higher propellant mass: 29.7 tons and a thinner diameter: 1.52 m. It was estimated that with the technologies available in Europe a structural index of 11% including margin is realistic.

5.2. *Thrust law*

In total, 13 different strap-on booster types, with propellant loading varying between 20 and 45 tons, have been studied. These boosters can be sorted in three categories.

The first one corresponds to medium strap-on boosters with a propellant loading between 30 and 33 tons and a long burn time between 90 and 120 seconds. These boosters were designed with a diameter of 1.52 m, and considered as evolutions of the GEM-60 booster of ATK. For boosted configurations, two of these SRMs are attached to the first stage. The P20 type 1 is also considered to be part of this first category even if four of this strap-on booster are ignited together at lift-off for configurations based on it. The thrust history of these boosters is plotted in Figure 5. The strategy followed to design the thrust law is similar to the one described in Figure 1. However the thrust law of the first stage was also taken into account in order to avoid that the sum of the thrust provided by the first stage and the booster leads to too high loads.

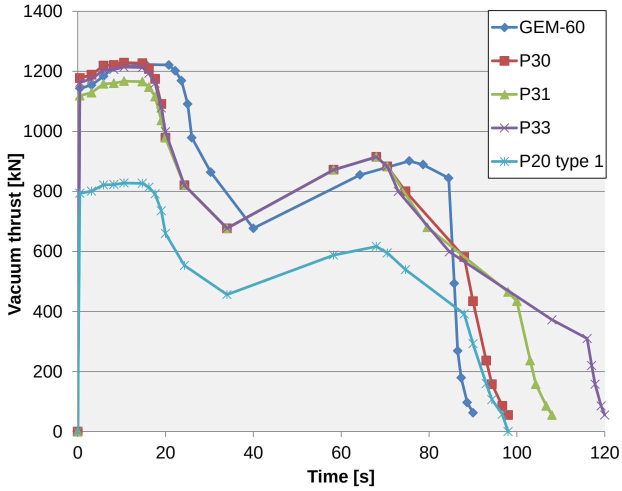

Figure 5: Vacuum thrust history of medium strap-on boosters with long burn time

The second category corresponds to big strap-on boosters with a long burn time. They are also designed to be ignited at only lift-off and used in pair. Their propellant loading varies between 40 and 45 tons. They have been designed in a second time, when the diameter of the TSTO launch vehicle has been increased from 3 m to 3.5 m, leading to a sizable increase of the drag. As they are combined with first stages already designed to facilitate the design of the booster, their thrust law is relatively simple compared to those of the smaller boosters previously described. Their diameter has been set between 2 m and 2.2 m. Further studies will be done to confirm the feasibility of the thrust histories, which are plotted in Figure 6, in combination with the chosen diameter.

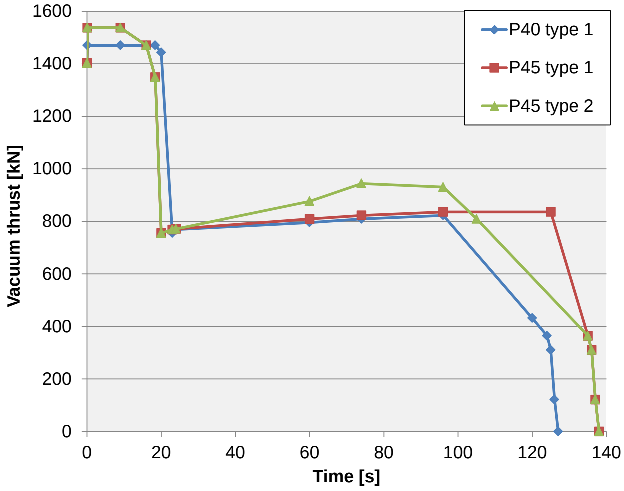

Figure 6: Vacuum thrust history of big strap-on boosters with long burn time

The last category is made out of the smallest boosters with propellants loading between 20 and 23 tons. Contrary to the others, they are all characterized by a relatively short burn time, i.e. between 65 s and 72 s. Their thrust histories are plotted in Figure 7.

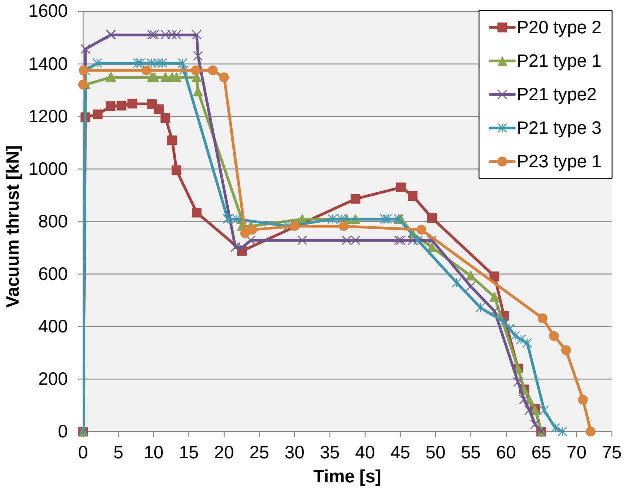

Figure 7: Vacuum thrust history of small strap-on boosters with short burn time

Indeed these boosters have been designed to be used by group of four. Two of them are ignited on ground with the first stage. After burnout, they are separated and the two remaining boosters are ignited. These two last boosters remain attached to the first stage after their burnout which occurs only few seconds before the burnout of the first stage. The goal of this unusual ignition strategy is to provide a boost surplus to the launcher which would not be possible with a unique pair of solid rocket boosters ignited on ground. Indeed the first pair of booster provides a high thrust surplus during the phase 1 (see Figure 8), then the thrust decreases to avoid a too high maximum dynamic pressure (phase 2). Due to grain geometry limitations the thrust level of the boosters is almost constant or slightly increasing before it decreases sharply (phase 3).

The second pair of boosters is then ignited during the third phase. The high thrust surplus provided by the booster ends prior to the end of the phase 3, in order to avoid a too strong increase of the maximum acceleration. Then the phase with constant or slightly increasing thrust extends during the end of the third phase and a beginning of the fourth phase. During this phase a moderate increase of the maximum acceleration is difficult to avoid. During the rest of phase 4 and phase 5, the thrust surplus decreases until it vanishes.

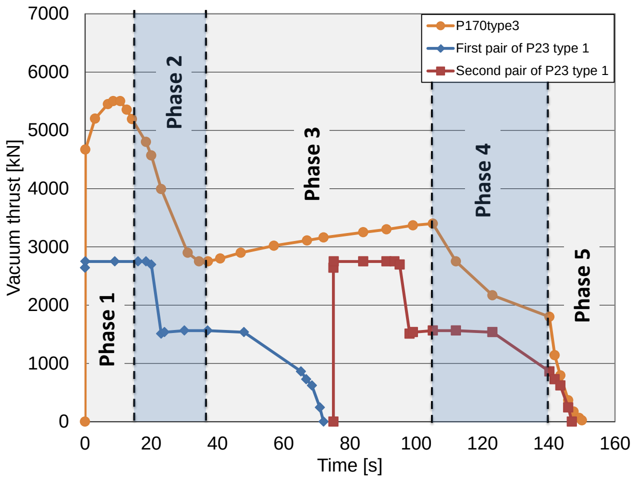

Figure 8: Thrust history design strategy for booster with delayed ignition

As stated for the first stage, the maximum combustion pressure for the boosters has been set to 90 bars. In some cases this pressure is however lower to allow a longer burn time. The HTPB1912 propellant has been selected with a finocyl type grain shape. The nozzle expansion ratio was set to 16, that is to say the same as P80 FW; it has not yet been optimised.

As for the first stages, computations have been done to determine grain geometries approaching the desired thrust laws and to confirm the chosen booster diameter.

6. Preliminary sizing of the upper stage

6.1. Subsystems

For all studied configurations, the same subsystems have been taken into account. Only the propellant mass and the tank diameter change from one configuration to the other. All subsystems masses were estimated based on heritage. For instance the pressure control assembly, the actuators and the reaction and control system propellant mass are based on data available on Ariane 5 ME upper stage. The engine thrust frame for the upper stage is also derived from this launcher. The avionics is based on Vega but is duplicated. The goal is indeed to reuse as much as possible existing equipment, in order to create synergies. Other masses like electrical lines were determined with the help of the DLR mass estimation program STSM. A margin of 10% has been added, to take into account modifications required for existing components to be adapted to the TSTO launch vehicle.

6.2. Structure preliminary sizing

The common bulkhead architecture has been selected for the cryogenic tanks of the upper stage. Previous analysis showed that this architecture makes a lighter and compacter structure possible even when the isolation of the common bulkhead is considered [5]. Propellant loadings between 24 and 29 tons have been studied. For each configuration (combination of first stage, upper stage and boosters), a preliminary sizing of the upper stage has been done. The pre-design was performed as follow.

First the propellant feed system has been pre-designed with the help of the SART in-house tool PMP (Propellant Management Program). The dimensions of the tanks, the geometrical and thermal residuals were determined. At this point the performance reserves were also estimated. A preliminary design of the pressurisation system was also performed, it includes the determination of the tank pressures and the mass of pressurisation gases: GHe (gaseous helium) for the LOx tank and GH2 (gaseous hydrogen) for the GH2 tank.

With the help of the data previously computed with PMP and the characteristics of the ascent trajectory, a preliminary tank structure sizing was performed with the SART in-house programme LSAP (Launcher Structural Analysis Program). This preliminary structural analysis was done only for the upper stage. For the configurations with a diameter of 3 m studied in the early 2011 [5], an early version of LSAP was used. All configurations based on the increased launcher diameter of 3.5 m were pre-sized with the version 0.9 of LSAP. The principles remain the same as before: the launchers are treated as 1-dimensional bending beam with rotational symmetry and analytical procedures are uses to assess the structural mass. But additional features have been added, and the accuracy of the mass estimation has been increased.

The determination of the structural mass is done by considering the following standard load cases:

- Launch pad, fully fuelled and pressurised, wind/gust loads
- Maximum dynamic pressure (max q)
- Maximum product of dynamic pressure and angle of attack (max qα)
- Maximum acceleration (for configurations with boosters maximum acceleration prior to boosters separation) (max n_x)
- Maximum acceleration after booster separation (only for configuration with boosters) (max n_{x2})

To account for dynamic loads, the axial accelerations have been increased by 1.0 g for the max q and the max qα cases and by 1.25 g for the maximum acceleration cases. In addition 10% margins have been added to the computed masses.

6.3. Influence of the SRM on the structural index of the upper stage

The main goal of this structural analysis was to assess in what extent the loads resulting from the thrust history of the different first stage and booster combinations influence the mass and as a consequence the structural index of the upper stage. Note that all structural indexes given for the upper stage do not take the mass of Vinci into account.

A preliminary structural sizing has been done for 13 different H26 upper stages, all characterised by the same diameter of 3.5 m. They all correspond to different first stage and strap-on boosters combinations. Three parameters directly or indirectly influenced by the thrust laws of the first stage and strap-on boosters have been considered: the maximum acceleration, the maximum dynamic pressure and the maximum product of the dynamic pressure and the angle of attack.

As seen in Figure 9, it appears that higher acceleration leads to higher structural indexes. However it also appears that for a given maximum acceleration very different structural indexes can be observed. For instance, for two configurations with both a maximum acceleration around 4.3 g: P170 type 3 + H26 and P170 type 4 + H26, the structural index (excluding engine mass) varies between 11.5% and 13.0%. These two configurations encountered very different maximum dynamic pressure and maximum product of the dynamic pressure and the angle of attack. For the P170 type 3 + H26 configuration, q_{max} is 42.2 kPa and $(q\alpha)_{max}$ is 383.6 kPa.deg. For the P170 type 4 + H26 configuration, q_{max} is 67.4 kPa and $(q\alpha)_{max}$ is 467.7 kPa.deg.

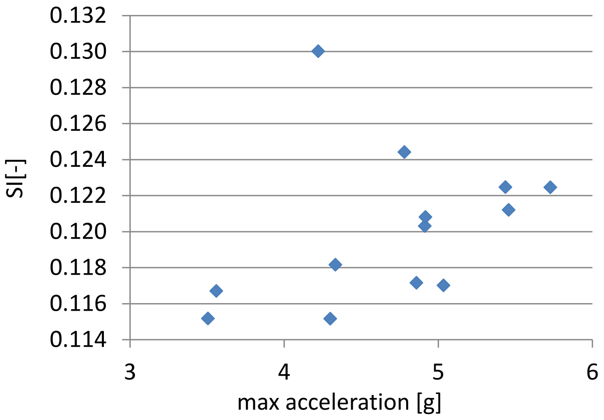

Figure 9: H26 upper stage SI vs. maximum acceleration

The influence of these two parameters on the structural index can be seen in the Figure 10 and Figure 11. In both cases an almost linear tendency can be seen between the maximum dynamic pressure/the maximum product of the dynamic pressure and the angle of attack, and the structural index.

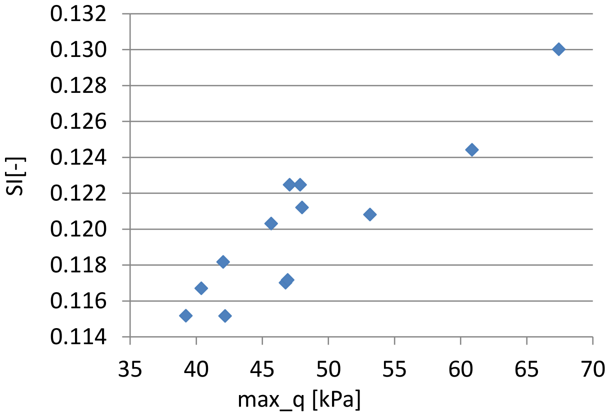

Figure 10: H26 upper stage SI vs. maximum dynamic pressure

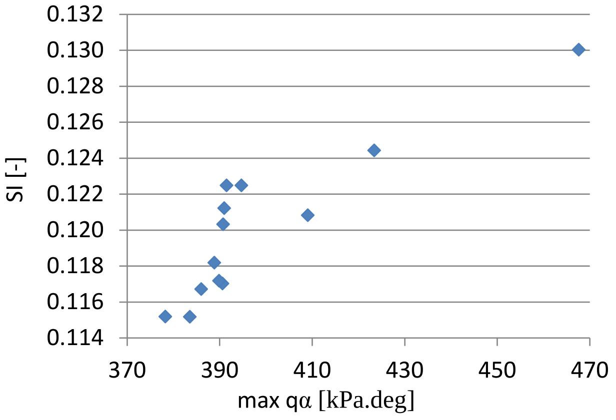

Figure 11: H26 upper stage SI vs. maximum qα

Even if the maximum acceleration, the maximum dynamic pressure and the maximum qα are not completely independent from each other, they all have to be considered carefully during the design of the thrust law of the first stage and the strap-on boosters. It seems however that the structural index of the upper stage is more sensible to the maximum dynamic pressure and the maximum product of the dynamic pressure and the angle of attack than to the maximum acceleration.

In the case of the TSTO launch vehicle, the same upper stage should be used for the versions with and without boosters in order to reduce complexity and cost. In all the cases presented here the most demanding mission for the upper stage corresponds to the version with boosters. Naturally this upper stage is heavier than the optimum stage for the clean version of the launcher (i.e. the version without booster). As a consequence to avoid a too dramatic diminution of the performances of this latest version the loads have to be kept as close as possible to each other in both versions (with and without boosters).

7. Performances

In order to assess the performances of the different configurations, trajectory optimisations have been done with the help of the DLR software Tosca.

Table 2: Main characteristics of the ascent trajectory to GTO for TSTO launchers based on P160

First stage	**P160**	**P160**	**P160**
Upper stage	**H26**	**H26**	**H26**
Booster	**-**	**2+2 P21 type 2**	**4 P20 type 1**
Acc_max [kPa]	4.3	5.5	4.8
q_max [kPa]	42.0	48.0	60.9
q @ booster separation [kPa]	-	24.8	1.67
max qα [kPa.°]	388.9	391.0	423.4
Payload to GTO [kg]	**1325**	**2845**	**2695**
GLO mass [kg]	208310	304120	299325
Payload to GTO without boosters [kg]	**-**	**1250**	**1165**
US SI [%]	11.8	12.2	12.4

The main characteristics of the ascent trajectory of a selection of configurations based on P160 are summed up in Table 2. The first configuration was sized to be used only without booster. For this reason its upper stage has the lowest structural index of the three launchers presented in this table and a payload performance of 1325 kg which is a bit lower than the target. The two other versions of TSTO are pre-designed to be used both in a boosted and a clean variant. The first one used the delayed ignition strategy with 4 P21 type 2 strap-on boosters. It reaches a payload performance to GTO of 2845 kg which corresponds to the target. However when the boosters are removed the performance drops to 1250 kg, which is deemed as too low. The third configuration is designed to be used with 4 P20 type 1 strap-on boosters, it reaches a very high maximum dynamic pressure which has a negative impact on the structural index of the upper stage. The achieved reduction of the gravity losses (1285 m/s for P160 + H26 + 4 P20 type 1 instead of 1340 m/s for P160 + H26 + (2+2) P21 type 2) cannot compensate this increase of the structural mass of the upper stage. It results in a payload performance of 2695 kg for the boosted version and only 1165 kg for the variant without booster. These values are however deemed as to low compared to the target payload performances. For this reason it was decided to increase the propellant loading of the first stage to 170 tons.

Table 3: Main characteristics of the ascent trajectory to GTO for TSTO launchers based on different P170 first stage SRM

First stage **Upper stage**	**P170 type 1** **H26**	**P170 type 3** **H26**	**P170 type 4** **H26**
Booster	-	-	-
Acc_max [kPa]	3.5	4.3	4.2
q_max [kPa]	39.2	42.2	67.4
max qα [kPa.°]	378.3	383.6	467.7
Payload to GTO [kg]	**1420**	**1465**	**1245**
GLO mass [kg]	219240	219300	219470
US SI [%]	11.5	11.5	13.0

The main ascent characteristics for different P170 first stages combined with a H26 upper stage are summed up in Table 3. Due to the different thrust histories of these first stages, the encountered maximum acceleration varies between 3.5 g for the version based on P170 type 1 and 4.3 g for the TSTO launcher using P170 type 3. Similarly the maximum dynamic pressure varies from 39.2 kPa to 67.4 kPa and the maximum qα from 378.3 kPa.deg to 467.7 kPa.deg. The first two versions are very close in term of payload performance to GTO with 1420 kg and 1465 kg. The version based on P170 type 4 has however much lower performances. The decrease of the gravity losses (1520 m/s with P170 type 4 instead of 1625 m/s with P170 type 1 and 1600 m/s with P170 type 3) made possible by the high thrust level of the first stage cannot counteract the sharp rise in structural mass mainly explained by the high aerodynamic loads on the structures.

It was decided to select the P170 type 3 first stage motor for the study of boosted versions of the TSTO launcher. Indeed it is the SRM with which the highest payload performance has been reached. An overview of the characteristics of the ascent trajectory for boosted TSTO launchers based on P170 type 3 is given in Table 4.

Table 4: Main characteristics of the ascent trajectory to GTO for boosted TSTO launchers based on P170 type 3

First stage **Upper stage**	**P170 type 3** **H26**	**P170 type 3** **H26**	**P170 type 3** **H29**
Booster	**2+2 P23**	**2 P45 type 1**	**2+2 P23**
Acc_max [kPa]	4.9	5.0	4.8
q_max [kPa]	45.7	46.8	44.3
q @ booster separation [kPa]	14.1	0.03	13.7
max qα [kPa.°]	390.8	390.7	388.0
Payload to GTO [kg]	**3040**	**2710**	**3100**
GLO mass [kg]	323630	321150	326855
Payload to GTO without boosters [kg]	**1330**	**1420**	**1110**
US SI [%]	12.0	11.7	11.3

The two strategies for the boosters ignition presented previously were studied. In one case two big P45 type 1 strap-on boosters are ignited at lift-off and provide a thrust surplus during the main part of the burn time of the first stage. The second option is based on two pairs of P23 strap-on boosters. The first one is ignited on ground and the second one is ignited with some delay as presented in chapter 5.2. It can be seen in Table 4, that in both case the maximum acceleration, dynamic pressure and qα are very close. However the combination of these parameters leads to a different structural mass. The version of the TSTO launcher using the 2 pairs of P23 boosters has the heaviest upper stage. This drawback is however more than compensate by an advantageous thrust law and the reduction of the mass at the separation of the first pair of boosters. The P170 type 3 + H26 + (2+2) P23 (see Figure 12) has indeed a payload performance into GTO over 3 tons. The variant with 2 P45 type 1 cannot do better than 2710 kg. However when the booster are removed the version designed for the 2 P45 type 1 is the most advantageous, thanks to the lower structural index of its upper stage. Another drawback of the variant with two pairs of P23 boosters is the very high value of dynamic pressure at boosters separation. This point will have to be studied in more details.

No real optimisation of the propellant loading of the upper stage was done during this part of the study. However the performances were calculated for propellant loading of 27 tons and 29 tons. It shows, as already expected (see [5]), that the optimal propellant loadings for the boosted and the clean variant of a TSTO launch vehicle are different. For the clean variant based on P170 type 3 the optimum is situated slightly below 26 tons. For a boosted version, the maximum payload is reached for an upper stage propellant loading around 29 tons.

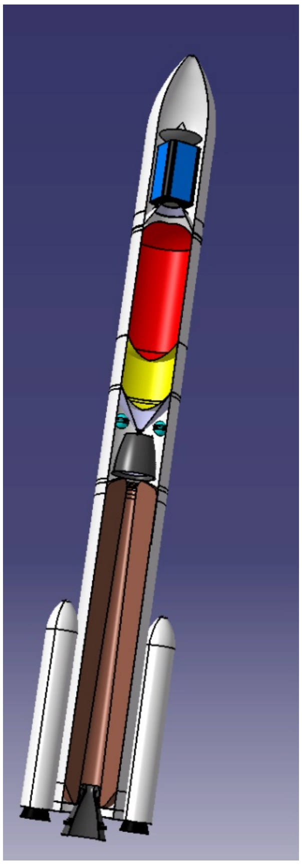

Figure 12: CAD view of the P170 + H26 + (2+2) P23

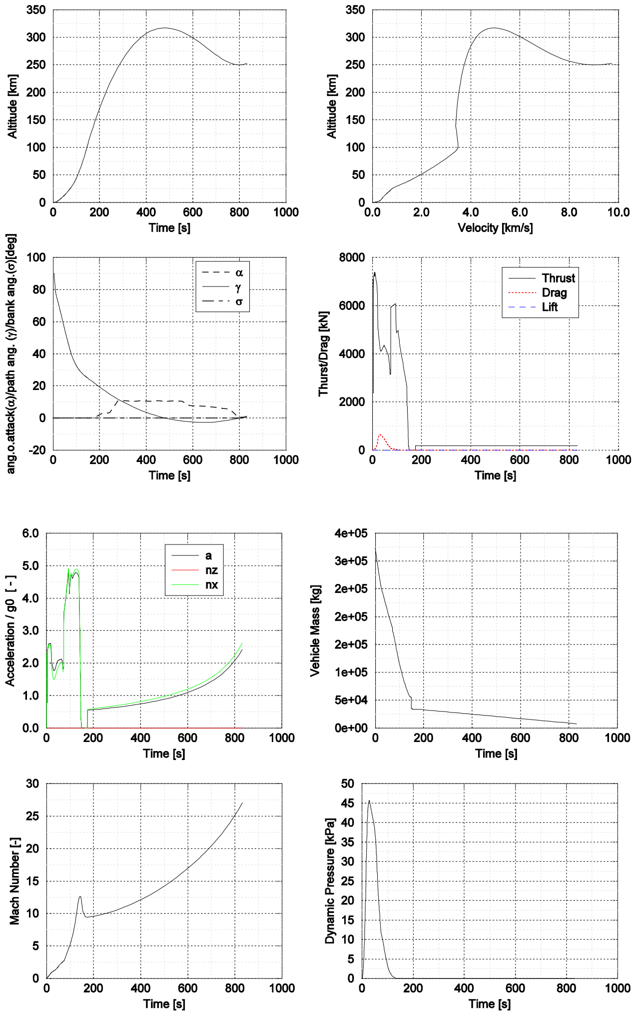

Figure 13: Ascent trajectory of the P170 type 3 + H26 + (2+2) P23 configuration

A CAD view of a P170 type 3 + H26 + (2+2) P23 is shown in Figure 12. The corresponding ascent trajectory to GTO is plotted in Figure 13.

The performances in SSO (700 km, polar circular) without modifications to the launcher have also been computed. P170 type 3 + H26 can put 3850 kg in this orbit. When 2 pairs of P23 are added the payload performance increased to 6380 kg. This is deemed sufficient for this orbit.

However the performance to GTO without booster is a bit low. An additional increase of the size of the first stage would be probably the easiest solution to achieve a payload performance to GTO of 1400 kg without booster. It may however be necessary to increase again the diameter to 3.7 m which corresponds to the maximum currently possible by the Guiana Propellant Plant. A decision concerning the choice of the booster ignition strategy will also require further studies.

8. Conclusions

After analysing the effects of several strap-on boosters and solid rocket motor first stage combinations, it has been seen that the design of their thrust histories plays a major role in the final performance and mission flexibility of the launcher. Different two-stage to orbit (TSTO) launcher configurations approaching the target payload performance of 1400 kg to GTO and 3000 kg to GTO with strap-on boosters have been proposed. These TSTO launch vehicles which rely on technologies and components already available in Europe would be able to create synergies with other on-going European programs. This new step in the design of a small TSTO launch vehicle confirms that this concept is promising, despite the increase of the diameter to 3.5 m, which was necessary to reduce the aspect ratio and problems linked to a long and narrow launcher. Two different booster ignition strategies have been studied. It has been determined that the addition of 2 P45 type 1 boosters to a P170 type 3 + H26 launcher would make possible an increase of the performances to GTO from 1420 kg to 2710 kg. Another solution based on two pairs of P23 boosters ignited with a delay demonstrated that even payload up to 3040 kg could be injected into GTO. This solution has however drawbacks: it has a negative effect on the P170 type 3 + H26 without boosters which is then not able to launch more than 1330 kg in GTO. Moreover the high level of the dynamic pressure at the separation of the first pair of boosters is challenging. Further studies will be needed to decide which of the booster ignition strategies should be chosen. The propellant loading of the upper stage will also have to be re-optimised. A slight increase of the performance of the variant without booster is still wished, as a consequence a small increase of the propellant loading of the first stage will be considered. In any case, it will not exceed 180 tons. Finally the behaviour of the launcher during different missions such as the effect of the ballistic phases on the upper stage will be studied. An assessment of the controllability of the selected launch vehicle is also planned.

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