In-flight rocket engine mixture ratio management for launcher performance improvement

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Abstract

Recent investigations have been performed on future liquid propellant upper stages to increase launcher performance. One option aims at improving the efficiency of loaded propellant consumption through in-flight mixture ratio (MR) management, the objective being to reduce as much as possible the part of propellant reserve induced by non-symmetrical depletion of the propellant species. In this paper, an algorithm is presented that enables to adapt the MR during flight in order to compensate the effects of an initial off-nominal MR on propellant consumption and reduce statistical unburnt propellant mass, using only punctual in-flight level sensors.

1. Introduction

For a given mission, a launcher is operated to reach the targeted orbit with a specified minimum probability. Assuming an upper stage equipped with a liquid propellant engine, an amount of the loaded propellant mass of this upper stage called the “propellant reserve” has to be saved so as to meet this requirement since launcher parameters that have an impact on launcher performance can be slightly off-nominal during flight (i.e. the values of these parameters can be slightly different than the predicted ones). Nevertheless, this propellant reserve is a shortfall regarding launcher performance, which justifies the recent investigations on propellant reserve reduction.

Among these launcher parameters, one of interest is the mixture ratio (MR) of the upper stage liquid propellant engine. Indeed, an off-nominal MR (assumed steady during the whole upper stage flight duration) leads to an unsymmetrical tanks depletion that results in the exhaustion of one of the propellant species before the other one. This premature exhaustion creates an unburnt propellant mass that has not been consumed to produce velocity increment (ΔV). Consequently, assuming all the other launcher parameters nominal, the targeted orbit cannot be reached because of this premature exhaustion if no propellant reserve has been saved. Therefore a part of the propellant reserve mentioned above is due to the potential in-flight MR deviation with respect to the value of this MR predicted on ground.

Recent studies have been conducted on future upper stages with enhanced capabilities with respect to previous designs. Among the features to be noticed is the capability to switch during flight from a first full thrust regime to a second lower thrust one. Taking benefit from this capability, the possibility to adapt the MR of the second thrust regime in order to compensate the effects of an off-nominal MR of the first thrust regime on propellant consumption is investigated.

This paper first defines the framework and the major inputs and constraints of the study. Secondly, an algorithm is derived which is capable of handling the available measurements aboard the launcher and, through simple process, to define a target MR for the end of the upper stage propelled flight phase. Through this algorithmic chain, the overall reduction of statistical unburnt propellant mass is targeted. Then a modelling of launcher propellant tanks depletion is presented that includes in particular the various sources of off-nominal depletion rates in order to assess the performance of this simple algorithm. Specific focus is made on these uncertainty sources in order to distinguish their respective contributions to the depletion. Then, the quantification of the actual launcher performance gain resulting from this propellant active management (PAM) process is presented assuming a typical 3-stages launcher with a cryogenic upper stage equipped with the new European re-ignitable VINCI engine and a GTO mission with direct de-orbitation. Finally, perspectives are proposed in order to further improve both the modelling and the performance of this process.

2. Framework, major inputs and constraints of the study

2.1 Launcher and mission profile

As mentioned previously, recent studies have been performed on future upper stages with enlarged capabilities with respect to former European upper stages such as the current Ariane 5 cryogenic upper stage ESC-A. Among the enhancements to be noticed is the new European re-ignitable VINCI engine, the thrust of which is almost three times higher than the thrust of the HM7B engine used on Ariane 5 ECA. Furthermore, this engine can switch during flight from a first full thrust regime to a second lower thrust one which can be seen as an opportunity to adapt in-flight the MR of the second thrust regime in order to compensate the scatterings coming from the first part of the boost.

This study is conducted on a mission profile taking benefit from the re-ignition capabilities of the VINCI engine. This mission consists in the injection of two payloads in geostationary transfer orbit (GTO) followed by the direct de-orbitation of the upper stage (US) after a ballistic phase. The figure 1 hereunder describes this mission profile with a focus on the US flight phase.

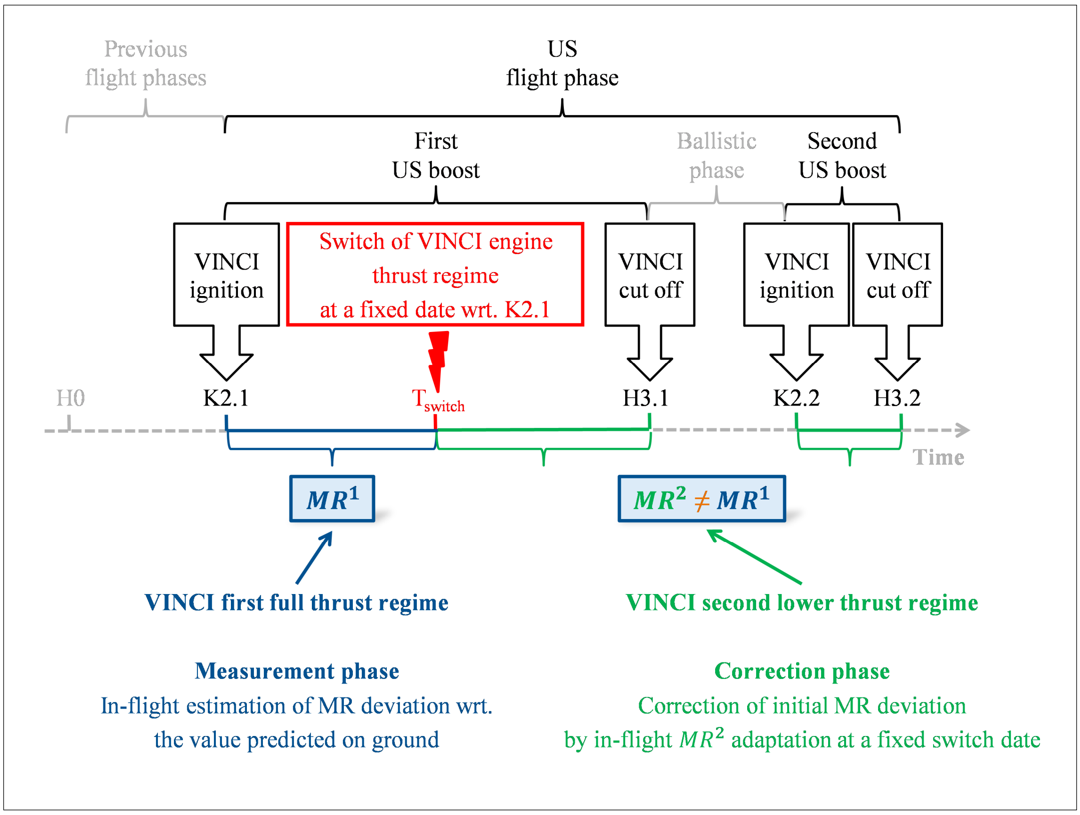

Figure 1: Mission profile

The figure 1 presented above highlights the fact that the US flight phase is composed of two different phases on both sides of the VINCI switch date:

- A first phase, before the switch date, corresponds to a VINCI first full thrust regime with a given MR. It is here designated as "measurement phase" since measurements aboard the launcher are processed so as to estimate the in-flight MR deviation with respect to the value of this MR predicted on ground.
- At the switch date, the VINCI engine instantaneously switches to a second lower thrust regime with a different MR, the value of which is adjusted through an algorithmic chain in order to compensate the potential in-flight MR deviation observed during the measurement phase. Hence, the second phase is called "the correction phase".

2.2 The two VINCI thrust regimes

In this study, it is assumed that VINCI thrust regime switch occurs at a fixed date with respect to K2.1 (i.e. with respect to the VINCI ignition date for the first US boost). In other words, no in-flight adaptation of this switch date is foreseen in the frame of this study. Therefore, the only way available to compensate the first phase MR deviation is to adapt the MR of the VINCI second thrust regime. Nevertheless, the adaptation range is limited because the value of the second thrust regime MR must remain inside the qualified domain of the VINCI engine. This is highlighted in the figure 2 hereunder describing the VINCI MR evolution with respect to time in US flight phase.

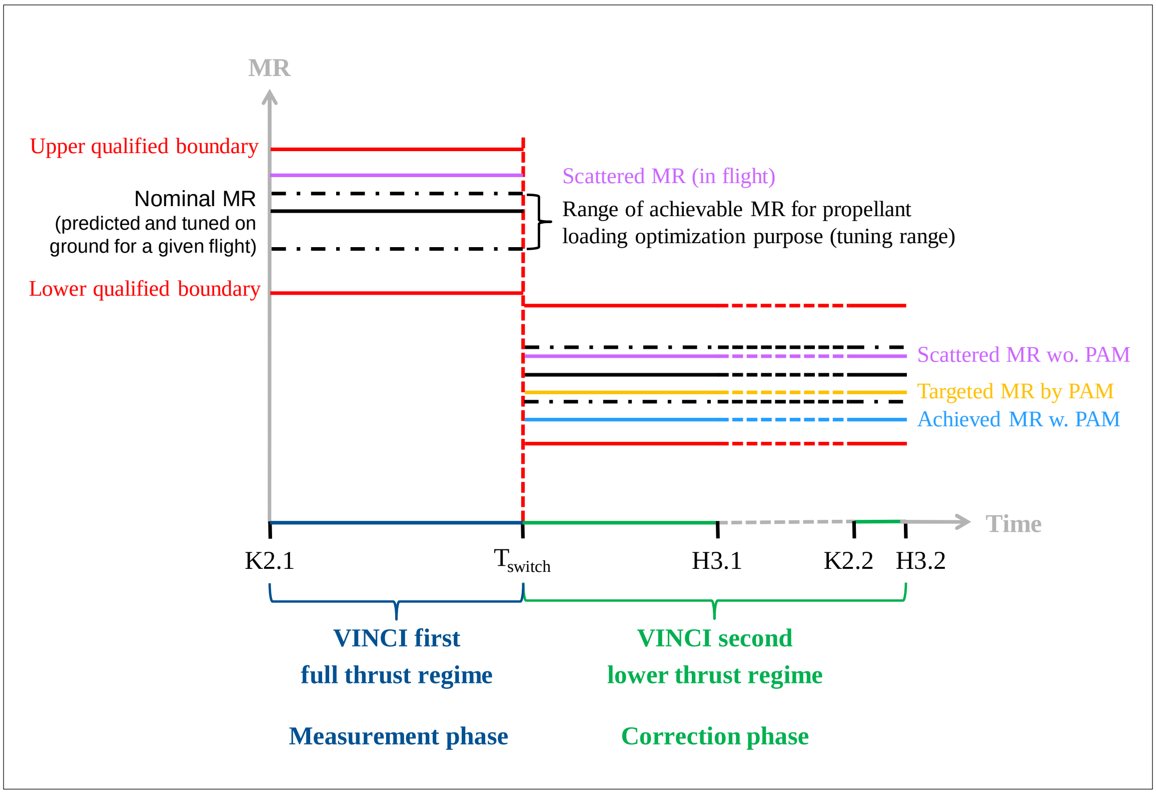

Figure 2: VINCI MR evolution with respect to time in US flight phase

On figure 2 are represented the main variables of interest involved in the PAM process investigated in this study:

- In red colour, are represented the boundaries of the VINCI qualified domain in terms of MR. In order to cope with in-flight MR scatterings, the tuning range of VINCI MR is necessarily narrower than the qualified domain.
- In black, the solid line represents the nominal MR, predicted and tuned on ground for a given flight. This MR can be chosen in the tuning range represented in dotted line in order to optimize propellant loadings with respect to the mission profile and targeted launcher performance.
- The MR in-flight value, here represented in purple, will be slightly different from the one predicted because of scatterings. Before switch date, this MR is the one to be estimated through the measurement and algorithmic chain of the PAM process.
- Based on this estimation, the target MR of the VINCI second thrust regime represented in yellow colour is computed by the algorithmic chain in order to minimize unburnt propellant mass. Nonetheless, as for the VINCI first thrust regime, the MR of the second thrust regime is also scattered because of the regulation valve position uncertainty. This scattered MR which is the one achieved in flight when PAM process is implemented is represented in blue.

In addition to the different aforementioned variables of interest, equation (1) defines the mean MR over the whole US flight steady state phase, which is the key variable that is used to assess the impact on launcher performance of the PAM process investigated in this study. Indeed, this variable alone represents the ratio in which propellant species are consumed and its scattering is used to size the part of propellant reserve induced by non-symmetrical depletion of the propellant species.

$$\overline{MR} = \frac{m_{LOx}^{1+2}}{m_{LH2}^{1+2}} = \frac{m_{LH2}^{1} MR^{1} + m_{LH2}^{2} MR^{2}}{m_{LH2}^{1} + m_{LH2}^{2}} = \frac{m_{LOx}^{1} + m_{LOx}^{2}}{\frac{m_{LOx}^{1}}{MR^{1}} + \frac{m_{LOx}^{2}}{MR^{2}}} \qquad \textbf{(1)}$$

Where:

- $\overline{MR}$ is the mean MR over the whole US flight steady state phase;
- MR^{1} is the mixture ratio of the VINCI first thrust regime;
- MR^{2} is the mixture ratio of the VINCI second thrust regime;
- m_{LOx}^{1+2} is the LOx mass consumed during the whole US flight steady state phase;
- m_{LH2}^{1+2} is the LH2 mass consumed during the whole US flight steady state phase;
- m_{LOx}^{1} is the LOx mass consumed in steady state before switch date, that is to say the LOx mass consumed in steady state when VINCI thrust regime is the first one;
- m_{LOx}^{2} is the LOx mass consumed in steady state after switch date, that is to say the LOx mass consumed in steady state when VINCI thrust regime is the second one;
- m_{LH2}^{1} is the LH2 mass consumed in steady state before switch date, that is to say the LH2 mass consumed in steady state when VINCI thrust regime is the first one;
- m_{LH2}^{2} is the LH2 mass consumed in steady state after switch date, that is to say the LH2 mass consumed in steady state when VINCI thrust regime is the second one.

2.3 Propellant reserve and PAM principle

In this section, we discuss the general principle of the PAM algorithm and more specifically the variables that are targeted by the algorithm. Figure 3 details the contributors of the propellant budget, highlighting the one of interest in the frame of this study:

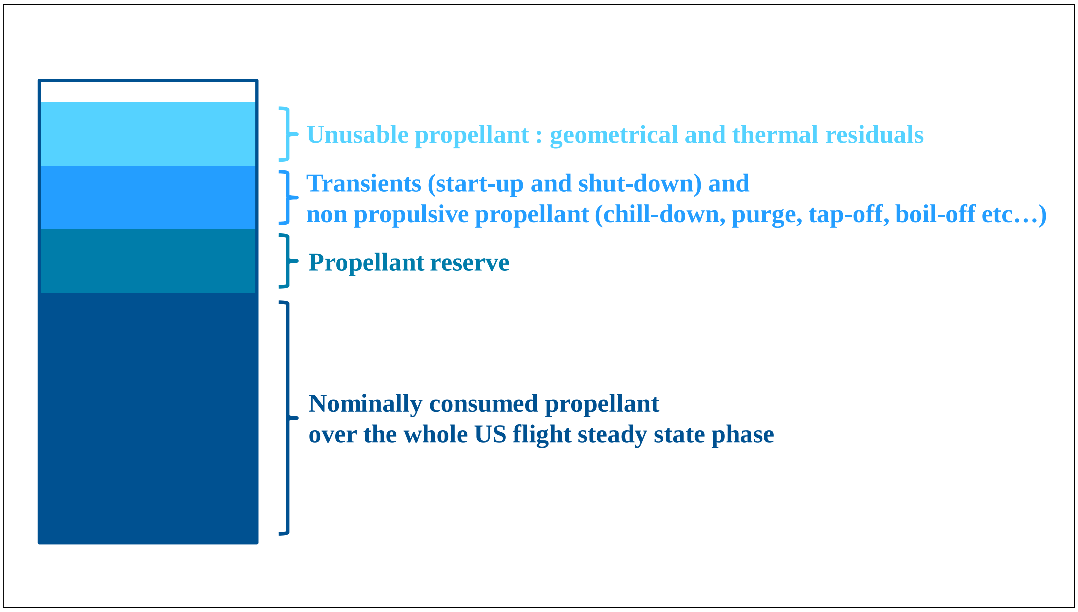

Figure 3: Schematic representation of an upper stage liquid propellant tank

As mentioned previously, for a given mission, a launcher is operated to reach the targeted orbit with a specified minimum probability. Due to in-flight scatterings, an amount of the US loaded propellant mass, called the propellant reserve, has to be saved so as to meet this requirement. Indeed, launcher trajectory, external environment as well as launcher parameters such as US dry mass and propulsive parameters or previous flight phases parameters can be slightly different in-flight than the predicted ones on ground. Reduction of these scatterings is not envisaged in the frame of the present work since they do not lead to large unsymmetrical tanks depletion i.e. to MR bias.

In fact, the main parameters of interest with respect to the objective of the PAM process investigated in this study are:

- Direct MR scatterings of the VINCI engine (not only for the first thrust regime but also for the second one), because they – logically – induce an asymmetrical depletion that the PAM algorithm will manage.
- Uncertainties of US LOx and LH2 loadings because they also induce a bias of the mean MR to target over the whole US flight steady state phase. Indeed, one understands that with a nominal MR and off-nominal loadings there will be unburnt propellants so that conversely an in-flight modification of the MR is required to minimize unburnt propellant mass. The fact that PAM principle is based on propellant level measurements will also help compensating US LOx and LH2 loadings uncertainties.

The PAM process investigated in this study aims at decreasing the scattering of the mean MR over the whole US flight steady state phase through measurement of the actual MR of the VINCI first thrust regime and in-flight adaptation of the MR of the VINCI second thrust regime.

3. Algorithmic chain and tank modelling

The previous sections introduced the major contributors to the upper stage propellant reserve, thus putting forward which one could be reduced through the use of propellant management chain. The goal of this section is to present an algorithm capable of handling the information provided by tank sensors and, through simple process, to define a target MR for the end of the US propelled flight phase. It is useful to recall here the two major assumptions underlying the work presented here: first the control of the engine MR only (with respect to a direct control of mass flow rate for instance), second the fixed switch date at which the MR would be modified.

This framework being set, one first has to define what information is available on board so as to identify the possible data processing that can be implemented in a MR management algorithm. Then, the performances of such an algorithm are to be assessed, which will require a modelling of the actual tanks depletion during flight, taking into account the various sources of uncertainties affecting the whole system.

With respect to the sensors available in the tank, an assumption has been made that only punctual level sensors can be used. This might be conservative with respect to what is available at the best, but would thus provide a first assessment of what can be achieved in terms of the minimum performance gain expected. Level sensors considered here are to be seen as discrete indicator, so that the signal will typically be either 1 (resp. 0) in the presence (resp. absence) of liquid in front of the sensor. Raw measurement provided by the sensors is a liquid level measurement, and not directly a mass measurement that would be our primary variable of interest. Furthermore, it is assumed in the following study that only one measurement is available in-flight, located somewhere in the tank inside the fill level range of the VINCI first thrust regime. The overall measurement setup described in here has actually been constrained by an existing tank definition.

As mentioned in section 2.3, the objective of the PAM process investigated in this study being to control the mean MR during the flight, the crucial information to have at disposal is the actual propellant mass remaining in each tank at the thrust regime switch date, which coincides with the instant at which a control on the MR valve is authorized. Indeed, such information would allow defining what MR is to be targeted in the subsequent flight phase in order to minimize the unburnt propellant mass resulting from MR deviations. However, since level sensors are punctual, they cannot perform in practice a measurement at the date of the thrust switch – in particular due to the uncertainties affecting the depletion level at this date. Moreover, a certain range of mission implying various initial propellant loadings is to be covered by the launcher under consideration, so that for a given switch date the fill level in a given tank will vary from one mission to another. All in all, it has been considered that the propellant level information at the switch date was not available, so that it had to be reconstructed from in-flight measurements.

The actual extrapolation procedure used in this study is fairly simple. Starting from:

$$\hat{M}_{Tswitch} = M_{Tmeas} - \hat{Q}\left(T_{switch} - T_{meas}\right) \tag{2}$$

Where $M_{Tswitch}$ is the remaining mass in tank at the switch date to be estimated, M_{Tmeas} the remaining mass in tank at the measurement date, Q the mass flow rate (assumed steady during each thrust regime steady state) to be estimated too, T_{switch} the switch date and T_{meas} the measurement date, one has to put forward several things. First, in this equation, the only real measurement is the T_{meas} because during the flight, the information provided by the level sensors will indeed be the date at which their status changes from 1 to 0. For the other variables:

- The mass M_{Tmeas} corresponding to the sensed level will be determined off-line using typically nominal tanks and propellants characteristics. It will thus be regarded as an uncertain parameter since it will likely be different in-flight from its predicted value.
- The mass flow rate Q would have to be estimated through another manner, using basically the same formula as (2) but with a predefined initial mass M_{MIS} corresponding to the forecasted mass at T_{MIS} which is the date of the beginning of the VINCI full thrust regime steady state. The mass flow rate estimation thus becomes:

$$\hat{Q} = \frac{M_{MIS} - M_{Tmeas}}{T_{meas} - T_{MIS}} \tag{3}$$

Where T_{meas} still is the measurement date, i.e. the instant at which the level sensors status changes from 1 to 0.

From there an estimation of the remaining mass at switch date can be drawn, which is the basic information allowing the in-flight determination of the MR to be targeted for the VINCI second thrust regime. Indeed, considering that a given amount of each propellant species is nominally burnt during the flight, one can define the MR at the second thrust regime that would lead to the desired consumption and thus cancel the effect of a first thrust regime MR deviation. Let $MREF_i$ be this reference consumption for the species “i”, $M0_i$ be the off-line forecasted initial mass of species “i” and MS_i be the in-flight estimated mass at switch date of species “i”, then the target MR of the VINCI second thrust regime to cancel a first thrust regime MR deviation can be defined as follows:

$$MR^{2}_{target} = \frac{MREF_{LOx} - \left(M0_{LOx} - \hat{M}S_{LOx}\right)}{MREF_{LH2} - \left(M0_{LH2} - \hat{M}S_{LH2}\right)} \tag{4}$$

Formula (4) can be seen as the output of the PAM algorithm. Another post-treatment can still be necessary which consists in a saturation of the commanded MR in order to be compatible with the actual tuning range consistent with the VINCI qualified domain. Finally, in-flight behaviour of this PAM algorithm is described by figure 4.

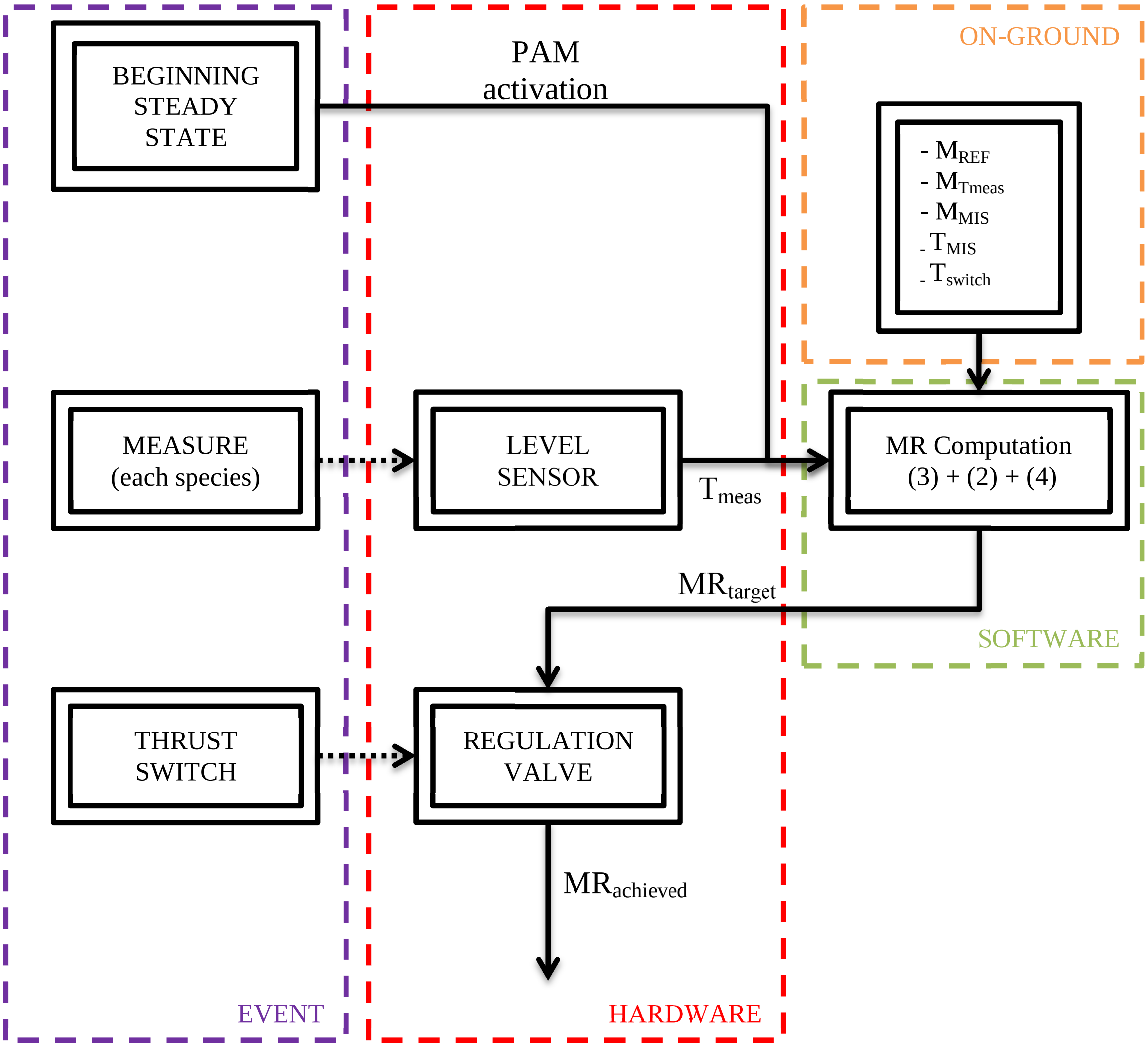

Figure 4: In-flight behaviour of the PAM algorithm

The performance of this simple algorithm is then to be assessed by simulating its behaviour in front of a tanks depletion model that takes into account various sources of discrepancies between what is nominally measured in-flight by the algorithm and what would be actually encountered in-flight. For this purpose, detailed investigations on the potential sources of in-flight uncertainties have been done, that put forward the major inputs listed hereafter:

- Tank geometry is subject to uncertainties associated to its manufacturing and thermal environment;
- Propellant characteristics also vary in function of their conditioning at lift-off (e.g. temperature) and of its evolution during the flight phases that precede the US flight phase of interest;
- Measurements are not perfect, mainly for two reasons: the level sensors might not have been positioned at the exact location on the tank wall as foreseen (manufacturing & assembly accuracy) and moreover, their signals can be affected by noises and bias that induce slight corruption of the raw information;
- Initial tank loading at lift-off is not perfectly predictable as on one hand the filling sensors are also subject to uncertainties and on the other hand, the filling level systems necessarily have limited accuracy;
- Engine global mass flow rate and MR are of course not perfectly known for each regime.

All these contributors lead to modifications on either the time duration separating the beginning of the VINCI full thrust regime steady state from the instant at which the level sensor is reached or the actual masses corresponding to a given in-flight level. To be noted that some of these uncertainties have been assumed as correlated between the beginning and the end of the flight (typically the tank geometry uncertainties), while others are not (for instance measurement scatterings). Finally, these different inputs have been modelled as Gaussian variables in order to allow for statistics post-treatment (see section 4).

From all these data it is then possible to define for each species, the actual time interval Δt between the beginning of the VINCI full thrust regime steady state and the measurement date that will be measured by the algorithm and fed into mass flow rate estimation process and subsequently to MR targeting process, that is :

$$\Delta t = \frac{M0_i - M1_i}{Q_{real}} \tag{5}$$

With $M0_i$ the actual initial mass at the beginning of the VINCI full thrust regime steady state, $M1_i$ the actual mass that will be measured taking into account all the uncertainties listed here above, and Q_{real} the actual mass flow rate for the species “i” considered.

Adding to this modelling a final scattering related to the accuracy of the MR valve in response to a MR command coming from the algorithm provides a simulator necessary to derive performance evaluation. For this purpose, thousands of Monte-Carlo are drawn in order to assess statistical mean MR with PAM and compare it to the case without PAM. This is addressed in the following section.

4. Launcher performance gain

The launcher performance gain resulting from the implementation of the PAM process investigated in this study depends on the following parameters:

- The switch date: in this study, it is assumed that VINCI thrust regime switch occurs at a fixed date with respect to K2.1. It is recalled that the only way to control the mean MR is therefore to adapt the MR of the VINCI second thrust regime. Another option would indeed be to adapt the switch date in order to exploit the fact that each thrust regime has a different MR, which allows to consider the switch date as a command to the mean MR. Alternatively, the switch date adaptation could be used to cope with saturation of the second thrust regime MR.
- The MR scattering of the VINCI first thrust regime: this is the deviation to be estimated and corrected.
- The MR scattering of the VINCI second thrust regime: this is the accuracy of the actuator which is here the MR regulation valve.
- The relation between the scatterings of both VINCI first and second thrust regimes: in this study, these scatterings are assumed to be independent, which implies that the only MR deviation that can be compensated is the one estimated during the measurement phase. It is important to precise that this assumption leads to the minimization of the launcher performance gain.
- The range of MR that can be targeted for the VINCI second thrust regime: this range is necessarily constrained in order to ensure that, despite scatterings, the achieved MR always remains inside the qualified domain of the VINCI engine.
- The accuracy of the whole measurement and algorithmic chain, that is to say the accuracy of both MR deviation estimation based on measurements and correction computation.

As mentioned previously, the key parameter that is used to evaluate this performance gain is the mean MR over the whole US flight steady state phase and especially its scattering which has an impact on the part of propellant reserve induced by non-symmetrical depletion of the propellant species. Therefore, a Monte-Carlo analysis is performed to evaluate the scattering of the mean MR over the whole US flight steady state phase with and without in-flight MR adaptation and the performance gain is finally assessed through the comparison between statistical unburnt propellant mass with and without in-flight MR adaptation. This method is schematically described in the figure 5 below.

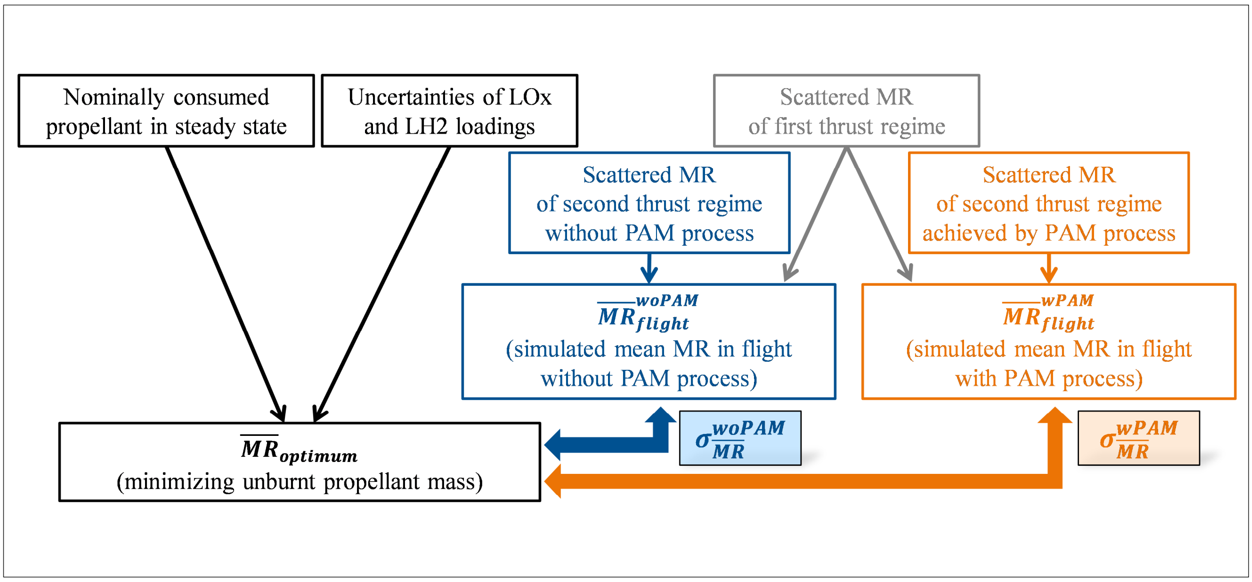

Figure 5: Method used to evaluate the performance gain

Considering the application case mentioned in introduction, first a test case is run without any uncertainty except for the one of the VINCI first thrust regime MR leading to the following results:

- It is checked that using the PAM algorithm, the actual mean MR dispersion $\sigma_{\overline{MR}}^{wPAM}$ is reduced to zero when the adaptation of the VINCI second thrust regime MR is assumed totally free. This enables to check that PAM algorithm finds the optimal solution in terms of mean MR if its measurements and action means are perfect.
- When limiting the reachable range of the second thrust regime MR (typically using a saturation), one finds that $\sigma_{\overline{MR}}^{wPAM}$ is already non null which proves that, for the switch date assumed in this study, the actual control range of the second MR is not wide enough to be able to correct any kind of first thrust regime MR scattering.

Second, the complete case taking into account all uncertainties is performed leading to the following results:

- It is checked that the $\overline{MR}_{flight}^{woPAM}$ and $\overline{MR}_{flight}^{wPAM}$ distributions are both centred on the average of the $\overline{MR}_{optimum}$ distribution, which is consistent with the Gaussian assumption of variables.
- Then, it is observed that $\sigma_{\overline{MR}}^{wPAM} \leq \sigma_{\overline{MR}}^{woPAM}$ leading to a performance gain of about a few dozens of kilograms which depends on the assumptions of this study such as the independence between the MR scatterings of both VINCI first and second thrust regimes.
- Eventually, this performance gain is slightly greater when the adaptation of the VINCI second thrust regime MR is assumed totally free.

Third, an additional case is performed in order to analyse the impact on the performance gain of an increase of the MR scattering of the first thrust regime. The conclusion of this last case is that the performance gain is greater when this scattering is bigger. Therefore, for a given launcher, the interest of this PAM process may decrease after several flights if post-flight investigations lead to reduce engine MR uncertainties; however, this PAM process can also be considered as a way to reduce development risks regarding ground/flight MR scattering requirement and thus regarding launcher performance requirement.

5. Conclusion

Recent investigations have been performed on future upper stages with enhanced capabilities with respect to previous designs. Among the improvements to be noticed is the new European re-ignitable VINCI engine which can switch during flight between two thrust regimes. A collateral benefit from this feature is the opportunity to adapt in-flight the engine mixture ratio (MR) at switch date, in order to compensate the effects of an off-nominal MR of the first thrust regime on propellant consumption. A propellant active management (PAM) algorithm making use of measurements aboard the launcher for computing in-flight the MR of the second thrust regime has thus been investigated, with the objective of reducing unburnt propellant mass and thus increasing launcher performance.

More specifically, this PAM process aims at decreasing the scattering of the mean MR over the whole US flight steady state phase. Its principle is based on propellant level measurements on board, which also allow this PAM process to partly bring compensation of US LOx and LH2 loadings uncertainties. Investigations performed on this PAM process confirmed that its implementation could reduce statistical unburnt propellant mass and thus increase launcher performance through the reduction of the part of propellant reserve induced by non-symmetrical depletion of the propellant species. This performance gain was assessed to be about a few dozens of kilograms depending on the assumptions of this study, which is attractive knowing that these assumptions, especially the independence between the MR scatterings of both VINCI first and second thrust regimes as well as the low MR scattering of the VINCI first thrust regime, lead to the minimization of the launcher performance gain brought by such an algorithm.

Even if, for a given launcher, the performance gain resulting from the implementation of this PAM process may decrease after several flights if post-flight investigations lead to reduce engine MR uncertainties, this PAM process can be considered as a way to reduce development risks regarding ground/flight MR scattering requirement and thus regarding launcher performance requirement.

Further investigations are currently performed so as to improve both the modelling (sloshing modes management, relation between the scatterings of both VINCI first and second thrust regimes, etc.) and the performance (several measurement/correction loops instead of one, tuning of mass flow rate to also reduce the mass flow rate scattering in addition to the MR scattering, etc.) of this PAM process.