Day-of-launch wind biasing trajectory optimization impact on launch vehicles pre-dimensioning methodologies

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Abstract

Past studies led by CNES have evidenced the interest of wind biasing technique for trajectory optimization, in terms of angle of attack and nozzle deflection statistics. The compensation, through trajectory optimization of part of the wind induced perturbation, allows decreasing the need of commanded deflection and the probability to reach high angle of attack levels. Such technique can either be applied using a mean seasonal wind profile or a wind measurement performed before launch. This last option would allow reducing drastically the sizing loads for the structure, but it needs to be considered as soon as possible in the preliminary design phases of a launcher development. This paper proposes and validates adaptation of the sizing methodologies applied during phase 1 engineering loops of launcher developments, for both TVC deflection and general loads, to account for the beneficial effect of wind biasing techniques. A benchmark launcher is considered.

1. Introduction

In previous work led by CNES launchers directorate [1], a first impact study of wind biasing methods on trajectory optimization for European launchers was performed. Such methods, commonly applied on other launch systems (especially US launchers [2]), had never been envisioned in Europe, probably due to the relatively low level of altitude winds velocity in French Guiana, compared to higher latitudes.

Wind biasing simply consists in computing a relative velocity vector including wind velocity components (see Figure 1.1). The gravity turn process, which is applied during atmospheric phase of flight (after lift-off and pitch over manoeuvre) is then biased, aligning launch vehicle longitudinal access with this new relative velocity vector instead of the former one (which considered a fixed atmosphere wrt Earth). The trajectory optimization process remains unchanged except for this modification.

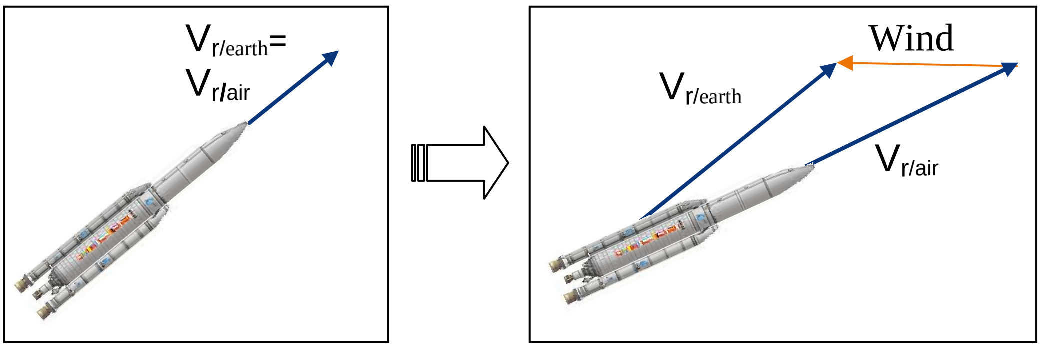

Figure 1.1: Gravity Turn For Trajectory Optimization Without (Left) And With (Right) Wind Biasing.

Two different approaches have been studied: the use of a seasonal mean wind to bias the trajectory optimization, and the use of a wind measurement performed as close as possible to the flight time.

It has been demonstrated that the use of a wind measured during launch chronology (typically 3 hours before launch) to bias the trajectory optimization, and consequently atmospheric phase attitude commands computation, could allow reducing the Q.α parameter of at least 50% (where Q is the dynamic pressure and α is the angle of attack). This parameter is the main driver of the lateral loads which are applied to the structure of the launch vehicle during the atmospheric flight. A reduction of about 25% of the maximum commanded deflection to the TVC actuators of launch vehicle was also observed. Table 1.1 illustrates such results.

Approach	**Parameter**	**Expected gain (%)**
Seasonal mean wind	99% Q.α gauge maximum	~15
Seasonal mean wind	TVC max commanded β	<10
Day-of-launch (3h)	99% Q.α gauge maximum	>50
Day-of-launch (3h)	TVC max commanded β	~25

Table 1.1: Quantitative Order Of Magnitude Of Wind Biasing Approach Impact

Such reductions probably depend on the launch vehicle benchmark characteristics, but are so significant that, if such methodology (called *day-of launch wind biasing*) was considered at the beginning of a launch vehicle development, a significant gain could be expected on structures and subsystems design. In a second step costs and mass savings can be expected. Such gains could help fulfilling the stringent objectives of new launchers development such as ARIANE 6

This paper presents a tentative adaptation of the launch vehicle pre-dimensioning methodologies to take into account the positive impact of the day-of-launch wind biasing. This adaptation concerns the so-called “phase 1” methodologies for both TVC control and general loads rough dimensioning.

The first methodology aims at dimensioning the maximum needed deflection and deflection rate of nozzles, and consequently the TVC subsystem characteristics. For Solid Rocket Motors it also drives the characteristics of the flexible joint, and for liquid propellant engines, the gimbal design. The second methodology aims at dimensioning the loads applied to the structural parts of the launcher (stages, skirts, booster attachments, etc.) through a first computation of a sizing Q.α gauge and mechanical fluxes.

Both these methodologies use simplifying assumptions and computations to ensure conservativeness in front of large set of unknowns at a preliminary step of development. Challenge is to ensure representativeness as well.

After a short presentation of the existing methodologies, proposed adaptations are presented, and then validated on the same launch vehicle benchmark as considered in [1], to ensure consistency with the expected impact on a developed launcher. Objective is to show that the statistical impact observed on the LV state parameters in a fully representative set of 6dof simulations (those presented in [1]) can faithfully be obtained on the results of the “phase 1” methodologies applied to the same launch vehicle.

Results from [1] are thus used as a reference to assess representativeness of the proposed approach (in other words, results from [1] are considered sufficiently faithful to actual flight expected results, to be a reference for preliminary design methodologies validation).

2. Phase 1 launch vehicle sizing Methodologies presentation

TVC Control deflection sizing

A point of interest in early launcher design phases concerns the control system sizing. Among options regarding control system architecture, a classical one consists in using Thrust Vector Control (TVC) on main propulsive stages, which would then be potentially completed by other systems in order to ensure satisfactory 3-axis control of the launcher.

Usual Phase 1 problem is to assess the deflection need at TVC level in order to provide preliminary requirements to both engines and actuation system designers, the goal being to ensure launcher concept feasibility as soon as possible in the design process.

To this purpose, computations are performed in order to assess the minimum nozzle deflection capability required to counter aerological disturbances during the atmospheric flight. Aerological phenomena taken into account in those calculations include wind shear and wind gust that can be encountered at various altitudes along the launcher trajectory. Methodology implies not to account for specific controller data, since the controller is usually not designed yet at this point of a preliminary development. Simplified approach has been developed to allow simple computation, combining the wind characteristics and launch vehicle physical characteristics.

Launcher sensitivity to wind disturbance in a given plane is directly linked to its intrinsic characteristics and to its trajectory. Classical controllability criterion [3] relates to the ratio between control efficiency and aerodynamic instability defined by the following equations:

$$K1 = \frac{T.Lp}{I} \qquad\qquad A6 = \frac{QSCN\alpha Lf}{I}$$

Where:

K1 is the control efficiency coefficient
A6 is the aerodynamic instability coefficient
T is the thrust
Lp is the lever arm between nozzle rotation axis and launch vehicle Centre of Mass (CoM)
I is the LV inertia wrt its CoM
Q is the dynamic pressure
S is the reference surface for aerodynamic coefficients
CNα is the derivative coefficient of lateral force wrt the angle of attack
Lf is the lever arm between aerodynamic centre of pressure and launch vehicle (CoM)

Indeed, those two parameters characterize the launcher rigid dynamics around its CoM in front of wind (inducing angle of attack) and provided a given amount of thrust deflection. A typical example of A6 and K1 coefficient evolution along the flight is presented on Figure 2.1 for a benchmark launcher. It is to be noted that this specific launcher exhibits satisfactory control efficiency compared to its aerodynamic instability, since K1 is more than twice the value of A6 throughout this flight phase. One can also remark than both K1 and A6 face significant variations with time, due to the strong unsteadiness of both the launcher itself and its environment, so that particular flight times are more demanding in terms of deflection than others.

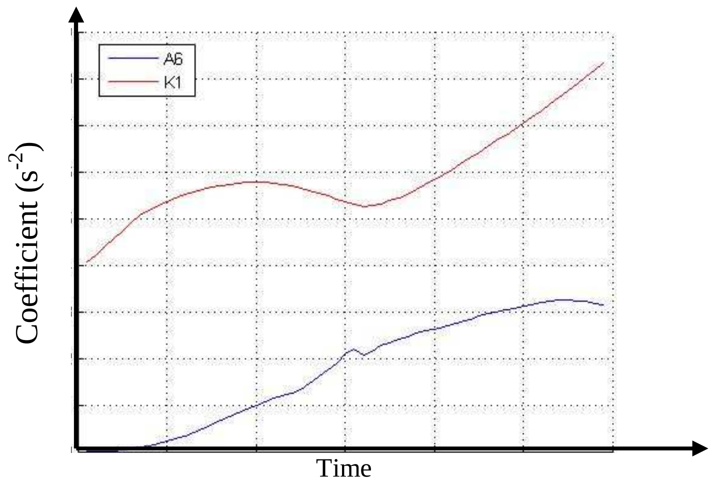

Figure 2.1: A6 & K1 coefficients of the benchmark launcher

Also, one can notice from their formulas that those coefficients are mainly related to launcher geometry, propulsion, aerodynamics and trajectory. Thus, means of improving launcher controllability usually ranges from adding aerofins in order to decrease the aerodynamic torque, up to deeper modification of the overall launcher design. Trajectory modifications such as dynamic pressure adaptation are also investigated on order to end-up with a satisfactory compromise at launcher system level.

Even if A6 and K1 give relative information on launcher needed control deflection, it is also much dependent on aerologic phenomena encountered during flight and more precisely on the wind shear profiles for which a link with required deflection need has been established. Indeed, a constant wind profile requires much less TVC deflection than a dynamic variation of the wind. Wind shears are thus considered for TVC deflection sizing: different thicknesses of altitude (atmosphere) are considered.

General loads sizing

The following preliminary data are used in phase 1 for the calculation of the general loads on the launcher:

- nominal trajectory: thrust, altitude, velocity, dynamic pressure vs. time ;
- mass and centring: global and distributed values at the main sections of the launch vehicle;
- aerodynamic database: global and distributed values based on the external shape
- wind database representative of French Guyana atmosphere.

All the 3 first sets of data are associated to a preliminary design of the launcher and are phase 0 or phase 1 loop results.

The launcher is supposed to be rigid, the wind acts perpendicularly to its longitudinal axis. The main difficulty of the general loads computation in preliminary phases of development concerns the non-availability of control law at such step of the project. It is thus necessary to do a preliminary assumption, which is called “perfect controller”: during all of the atmospheric phase of flight, the launcher is supposed to counteract instantaneously the aerodynamic perturbation by an appropriate TVC deflection to follow the optimal trajectory path. The consequence of this assumption is that there is no angular acceleration seen by the launcher.

The following state parameters of the launcher are computed under this assumption:

- angle of attack (AoA): it is supposed that the angle of attack is null just before the wind perturbation is applied, then the AoA seen by the launcher at the end of the perturbation is supposed to be the geometric one

  $$AoA = \text{atan}\,(Vl/Vw)$$

  Where:

  Vl is the launcher relative velocity wrt Earth
  Vw is the wind amplitude

- nozzle TVC deflection: computed to counteract the aerodynamic moment
- longitudinal and lateral load factors from the global loads projection in the longitudinal and transversal axis.

Aerodynamic perturbations considered are either constant wind amplitude or wind shear profiles.

Using these state parameters the general loads (normal and transversal load, bending moment and resulting longitudinal mechanical fluxes) are then computed by summation of the loads applied to the launcher stages: inertial loads, aerodynamic loads and thrust loads.

Some margins are added to take into account the non modelized phenomena (dynamic loads, aeroelasticity) and the uncertainties on the inputs.

Wind database for the sizing studies

From previous methodologies description, one can understand that sizing wind data are necessary to perform TVC control deflection and general loads phase 1 studies.

Statistics of wind amplitude (for general loads studies) and wind shears (for both TVC control and general loads studies) are performed on representative databases of wind profiles. Different thicknesses are considered for wind shears, from 100m to 3000m: it is justified by the fact that some of them affect more the launcher dynamics than others, and are thus more demanding in term of deflection, also generating AoA.

For qualification purpose, an extensive database is used containing more than 14000 wind profiles. This database is based on wind measurements. Since measurement means are not fully accurate at low wavelengths, these profiles are corrected adding a mesoscale component from a model to ensure that the database is representative of all winds characteristics. 14000 winds are necessary to ensure an acceptable statistical convergence of the results obtained in qualification, and permit to compute monthly statistical values to take into account the annual and cyclic variability of the aerology. The envelope of the monthly results is then considered.

This reference database is generated from wind measurements performed at 0h and 12h every day during some years: its use was obviously not possible in the objective of the evaluation of the day-of-launch wind biasing trajectory optimization for time intervals lower than 12h.

Another database, presented in [1] has thus been used. It contains around 1500 pairs of wind profiles, from ground to 15km and originated from CSG soundings, which have been corrected by the addition of a mesoscale model in order to obtain realistic winds, as these seen during flights. This database has been chosen because it contains wind pairs which have different time intervals lower than 12h (intervals cover from 30 minutes to 11 hours).

This database has been used as the first wind of each pair can be considered as a measured wind during chronology and the second one as a launch wind. In [1] the first wind was pre-treated and used for biased trajectory optimization, and the second one used in 6dof simulation to assess the launch vehicle state parameters during flight.

Figure 2.2 hereafter represents the 99% statistics of the 1500 second winds of each pair. Modules and shears for each 1km step altitude are statistically analysed, following the same procedure as the Q.α statistical analysis [1].

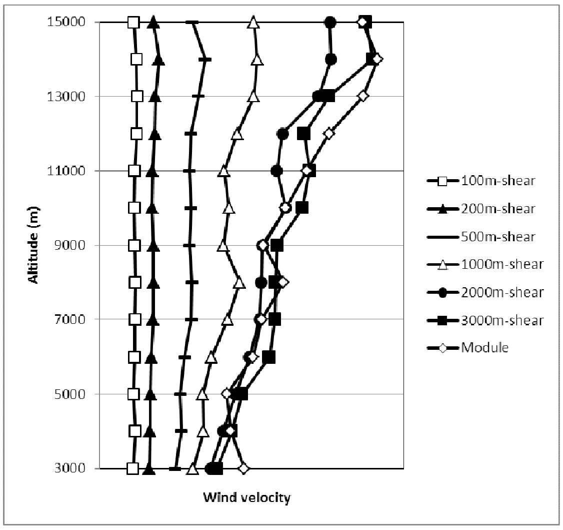

Figure 2.2: 99 percentiles of 1500 wind database parameters: module and shear over thicknesses from 100m to 3000m

Adaptation of the sizing studies' methodology

The proposed adaptation of the simplified methodologies for TVC deflection and general loads sizing in phase 1 of a launch vehicle development, is simple: to consider, in input of the computations, not the module and shear statistics over the wind database, but the statistics of the difference between 2 wind profiles separated by a given interval.

The 1500 pairs of winds have been used to compute the difference between each pair of profiles and then their statistics. This computation has been done at different altitudes and for various altitude thicknesses: between 100m and 3000m.

A sketch of the method is illustrated on next figure.

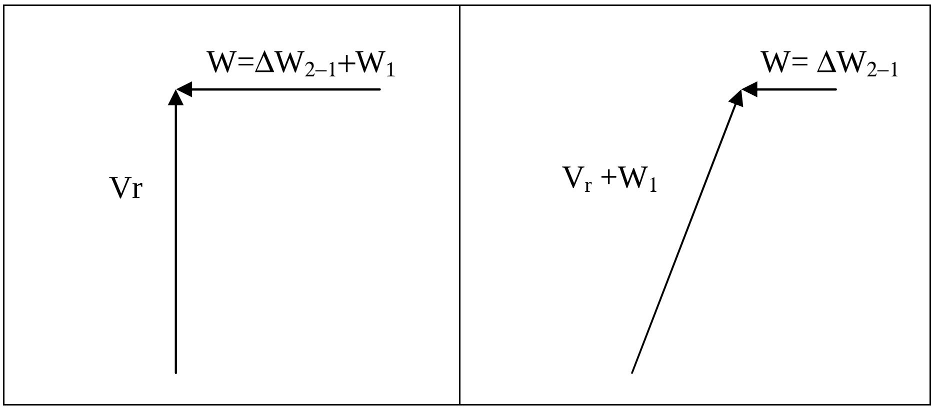

Figure 2.3: Method of wind statistics computation when considering day-of-launch trajectory biasing

Trajectory biasing considering the first wind profile of each pair will modify the relative velocity vector Vr of the launcher with respect to the air, thus partially compensating for winds perturbation. In Figure 2.3, the component represented as W_1 is measured prior to launch, and thus compensated for. However, the interval ΔT, that separates wind sounding from the lift-off, induces that the wind profile can evolve, so that an additional component, noted ΔW_{1-2} will be present at the moment of flight. The launcher will thus face some *residual* winds, despite the wind-biased optimization. The statistic computed between first and second wind of each pair correspond to the statistic of these *residual* winds.

Actually statistics are performed over the difference between a pre-treated 1st wind profile and the actual 2nd wind profile of each pair. As explained in [1], some pre-treatments are indeed applied on the wind profiles before they are used to bias the trajectory optimization.

These statistics are also adapted to account for the interval between 1st and 2nd wind profile of each pair. Actually, same hypothesis as in [1] is made, considering that *residual* wind characteristics (module and shears) follow a normal distribution, with a mean and standard deviation linearly depending on ΔT. Impact of the day of launch wind biased trajectory optimization can then be assessed for different durations ΔT between wind measurement and flight.

Figure 2.4 illustrates the 99% wind statistics for a time interval between first and second wind (i.e. between measurement and flight) of 3 hours. One can observe that these statistics evidence a large reduction when considering the module and the large altitude thicknesses shears (typically over 2000 or 3000m atmosphere layers).

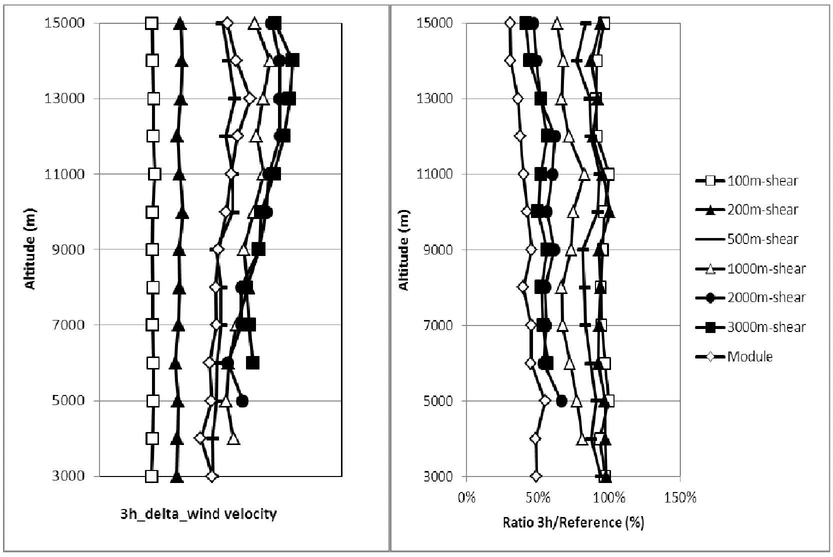

Figure 2.4: 99 percentiles of considered the difference between the first pre-treated wind and the second wind - ratio vs. absolute wind database

3 - Interest of "day-of launch" wind biased trajectory optimization for control deflection sizing

Updated statistics have thus been applied to the benchmark launcher, and the deflection needed to control them subsequently computed using the phase 1 trajectory. It should be highlighted that the methodology presented in section 2 has been strictly followed: only the wind shear statistics in input has been modified.

As a result of this process, typical deflection needs at maximal dynamic pressure period are presented on Figure 3.1, where the various curves correspond to different durations (ΔT) between sounding and lift-off. One can observe that pre-flight wind soundings performed more than 6 hours before flight do not lead to a reduction of the deflection need computed with phase 1 methodology, whereas soundings performed 90 minutes before flight evidence a gain on deflection in the order of 10%.

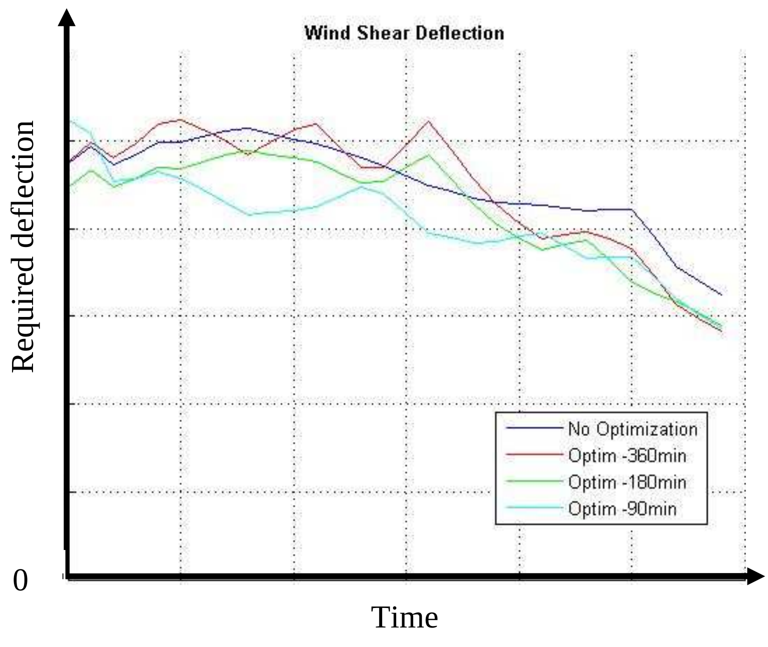

Figure 3.1: Deflection need depending on the duration between wind sounding and lift-off time

Despite expectations from fully representative simulations results (from [1] and presented in Table 1.1), it appears that wind-biased trajectory optimization would not lead to significant reduction of the deflection need estimated in preliminary design phases of launchers.

Investigations showed that the explanation of this statement comes from the fact that low wavelengths are filtered out from the wind measurement (1st profile of each pair), before the profile is used to bias the trajectory optimization. In [1] such filtering is justified as these wavelengths (the low wavelength) correspond to the one also exhibiting low persistence through time. Actually, it has been shown in [4] that wind variability is not to be the same for all wavelengths content of the wind: the more the duration between sounding and flight, the higher the limit between persistent and turbulent – meaning variable – wavelengths.

And the wavelengths which impact the most the dynamic control deflection are partly filtered out. Their statistics are not significantly modified when considering the difference between the 2 winds of each pair.

These results show the limit of a simplified approach used in preliminary phases of development for control deflection sizing. These simplified methods cannot (by definition) represent all the phenomena involved in a controlled launch vehicle dynamics, but focus on the main ones, which are not those impacted by wind-biased trajectory optimization.

4 - Interest of "day-of launch" wind biased trajectory optimization for general loads sizing

Q.α computations

In this paragraph, it is supposed that for each considered wind profile, the trajectory optimization was biased in front of the wind which was sounded 3 hours before the launch time. As in [1] and as in section 3 above, first measured wind is pre-treated in order to filter-out the wavelengths lower than 2000m, which represent the most probable non persistent components of the wind for this time interval, see [1]. An example of the profiles of a pair of winds from the database is shown on the Figure 4.1.

To follow the first optimized trajectory, the TVC commands are very low and the resulting lateral inertial loads are neglected, compared to those induced by real wind profile. As for the control methodology adaptation (see section 3 above), the angle of attack is the approximated by the one resulting from the difference between the real launch wind (second wind of each pair) and the pre-treated measured wind before flight (1st wind of each pair). This difference is called *residual* wind in the following paragraphs.

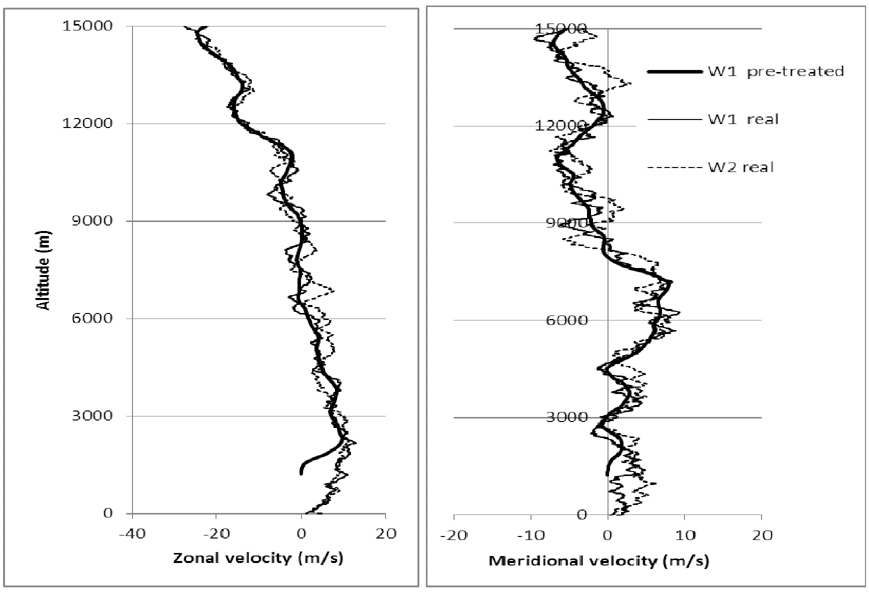

Figure 4.1: Example of wind pre-treatment. *W1 real* is the 1st wind the pair, *W1 pre-treated* is the one considered in trajectory optimization, and *W2 real* is the wind measured 3h later (considered as *launch wind*)

Then the angle of attack is calculated using these residual winds statistics. The Figure 4.2 shows the Q.α obtained using these 99 percentiles of residual wind parameters, compared to the results coming from the statistical analysis of the fully representative time domain simulations (from [1]).

Q.α predicted by the simplified approach is in the same order of magnitude as the reference one, and remains slightly conservative (roughly 5%).

Without wind biasing, the maximal Q.α was achieved around 13km of altitude, where the dynamic pressure is maximal. With wind biasing approach, the Q.α at this altitude is reduced of more than 50%, and the maximum is achieved at lower altitudes (it remains lower than reference one at the same altitude in any case). The explanation comes from the actual pre-treatment performed on the first wind before it is used in trajectory optimization for biasing: wind profile is truncated at low altitudes (before gravity turn is applied, for altitudes lower than 3km), as explained in [1]. This treatment produces thus fewer benefits on the Q.α at low altitudes. Activities are on-going to improve this situation in the future.

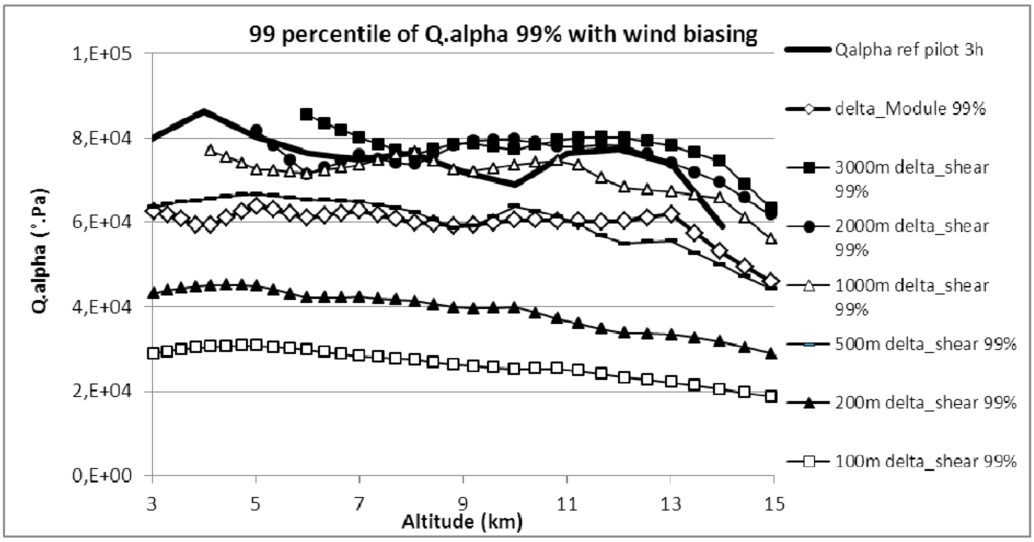

Figure 4.2 : comparison between the Q.α statistics from [1] and the simplified methodology results using 99percentile of *residual* wind shears and module

As a conclusion and contrary to the results for TVC deflection sizing in phase 1 (see section 4), the Q.α versus altitude profile is well estimated by the simplified phase 1 methodology when considering the envelope of Q.α induced by wind module and wind shears (up to 3000m thicknesses). This evidences that the wind biased trajectory optimization has an impact on one (at least) of the main phenomena involved in general loads sizing, and is thus faithfully reproduced by the simplified approach.

Impact on mechanical fluxes during atmospheric flight

Once the Q.α is known for each altitude layer of the atmospheric trajectory, the different components of the general loads can be computed (normal load, lateral load, bending moment) at the main launcher interfaces, to be used for the mechanical sizing of the structures. These components are combined to obtain the longitudinal mechanical flux.

The Figure 4.3 represents the compression flux obtained by the phase 1 general methodology as previously described at 3 different sections of the benchmark launcher, without wind biasing and with wind biasing:

- section 1: at the bottom of the fairing ;
- section 2: at the bottom of the skirt between 2nd and 3rd stages ;
- section 3: at the top of the skirt between 1st and 2nd stages.

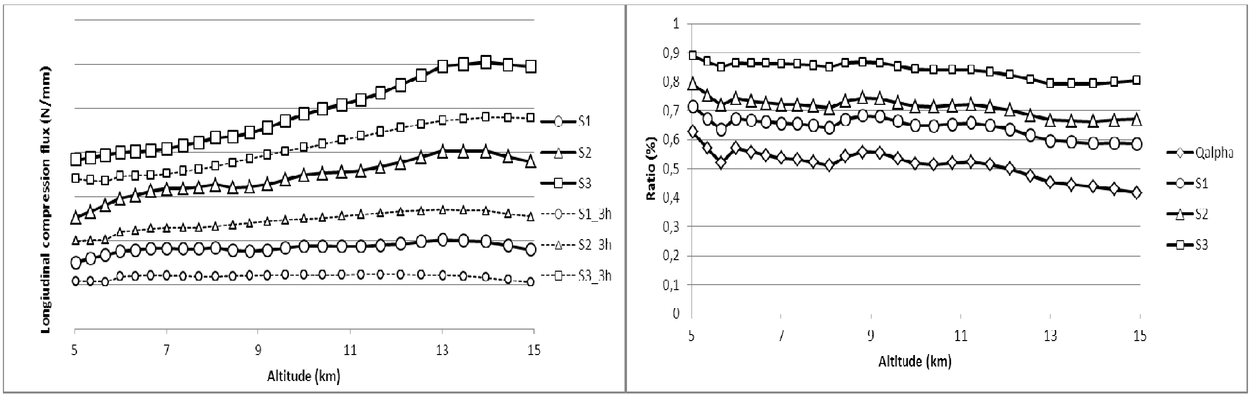

Figure 4.3: Impact of wind biasing trajectory optimization on the longitudinal mechanical fluxes on 3 sections of the launcher. Left: flux curve versus altitude. Right: reduction ratio induced by wind biasing.

It can be seen that the reduction of the mechanical fluxes curve during the atmospheric flight follows globally the reduction of Q.α. The gain is nevertheless lower than for the Q.α and is depending on the location of the sections: the more the considered section is close to the launcher fairing, the larger the reduction on the mechanical fluxes, because the lateral aerodynamic loading is the main contributor for these sections. For the sections more far away from the fairing, the normal load due to the longitudinal inertial effects become more important and the contribution of the lateral aerodynamic effects decrease in the total mechanical fluxes.

5 - Conclusion

In this paper was proposed and validated an adaptation of the existing (and used) methodologies for phase 1 engineering loops of launchers developments, to account for the beneficial impact of day-of-launch wind biasing technique in trajectory optimization. These benefits concern both TVC deflection sizing and general loads sizing.

Results obtained show that the benefits expected from this approach on TVC deflection sizing cannot be faithfully reproduced by a simple adaptation of the existing methodology. This can be explained by the fact that the wind biasing technique does not act on the main contributor to dynamic deflection during atmospheric phase of flight, and is thus neglected by the phase 1 methodology.

On the contrary, results show that the large and positive impact (more than 50% reduction) of the day-of-launch wind biasing technique is faithfully reproduced on the Q.α gauge by the phase 1 adapted methodology. Impact on the sizing mechanical fluxes are also presented for the considered benchmark launcher.

Preliminary results obtained on a test case representative of ARIANE 6 concepts tend to demonstrate that the expected gain on this launcher are similar to those obtained on the benchmark presented in this paper. CNES work will continue to confirm beneficial impact on ARIANE 6 design options in the future.

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