TVC Control, First Bending Mode and Aero-elasticity: Post flight reconstruction of VEGA LARES mission

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Abstract
This paper presents post flight analyses of VEGA launcher dedicated to reconstruction of first bending mode evolution. The link is made with the launcher model during the atmospheric flight (including elastic and aerodynamic models), the TVC control loop and its associated stability margins. The explanations based on identification of modal parameters and delay in the control loop as well as actuator nonlinearity are deemed unsatisfactory since not capturing the observed behaviour and leading to unrealistic values. The explanation more probable is the excitation by meso-scale component of the wind via aero-elastic model.

1. Introduction

The maiden flight VV01 of VEGA from Kourou on February 13th 2012, putting in orbit the LARES satellite as well as several microsatellites, has been a success. In the frame of the Level 1 exploitation campaign, the analysis of the Flight Data sent by Telemetry has been used to confirm assumptions and to explain phenomena of various disciplines and in particular to validate the GNC algorithms.

One of the main concerns of a Launch Vehicle mission is the Control during atmospheric flight especially the coupling with bending modes.

The analysis of Telemetry (both INS outputs used by GNC and additional sensors dedicated to flight reconstruction) allowed estimating the modal frequencies in particular the first mode frequency around 4 Hz, the most critical. The excitation of the first bending mode has been compared to the reconstruction of the Flight variables by a full 6 DOF simulator, taking into account post-flight model updating (propulsion, masses, atmosphere, sounding winds…). Differences have been observed in the amplitude level on angular rate.

After recalling the architecture of the VEGA Control algorithms in atmospheric flight and the values of the different parameters involved in the tuning (rigid mode, bending mode, actuators dynamics, sampling rate) we will explore several hypotheses to improve the fitting between flight and simulated data.

The first one is based on the closed loop behaviour of the TVC Control and the comparison with predicted stability margins. The conclusion is that this assumption is not sufficient to explain the behaviour of the bending modes.

The second assumption is based on aero-elastic excitation of the bending mode by the wind. It is likely that the excitation is produced by meso-scale components (between 50 m and 2000 m of wavelength) of the wind spectrum which lie in the modal frequency bandwidth.

The excitation due to the TVC deflection is also compared with the levels observed during the flight.

2. Post Flight Analysis

2.1 Available Data from Telemetry

The Post Flight Analysis is based on Telemetry data sent during flight. These data mainly are variables internal to Flight Program Software (in particular from GNC algorithms) and read on 1553 bus. They are collected in several Digital Messages sampled at the GNC sampling rate 25 Hz (40 ms).

Complementary data come from additional sensors specific for each mission. For instance for LARES flight (VV01), an additional INS (called LINS) was set at the inter-stage 1 / 2 to observe the first stage evolution after its separation. It delivers measurements at 3.9 kHz. For PROBA V flight (VV02) an INS and a GPS has been set to provide complementary measurements to be assessed for future use (Safety, Navigation).

For LARES flight, a set of accelerometers have been set on the launcher structure in order to analyse the dynamics response (from low frequencies up to vibration and acoustic frequencies). In particular for the low frequencies involved in the Control loop, modal identification and comparisons with predicted FEM data are possible.

2.2 Objective of Post Flight Analysis

The objective of the Post Flight Analysis Level 1 is to:

- identify the flight parameters (update the masses characteristics, the propulsion, the actuators, the elastic modes),
- explain all the observed phenomenon on different variables and in different disciplines (system and subsystems),
- replay the full mission as precisely as possible by a simulation on the full 6DOF non-linear model.

2.3 Observation of the 1st bending mode

The present analysis is focused on the 4 Hz oscillation observed during first stage flight on angular velocities (so-called P, Q, R) deduced from INS measurements.

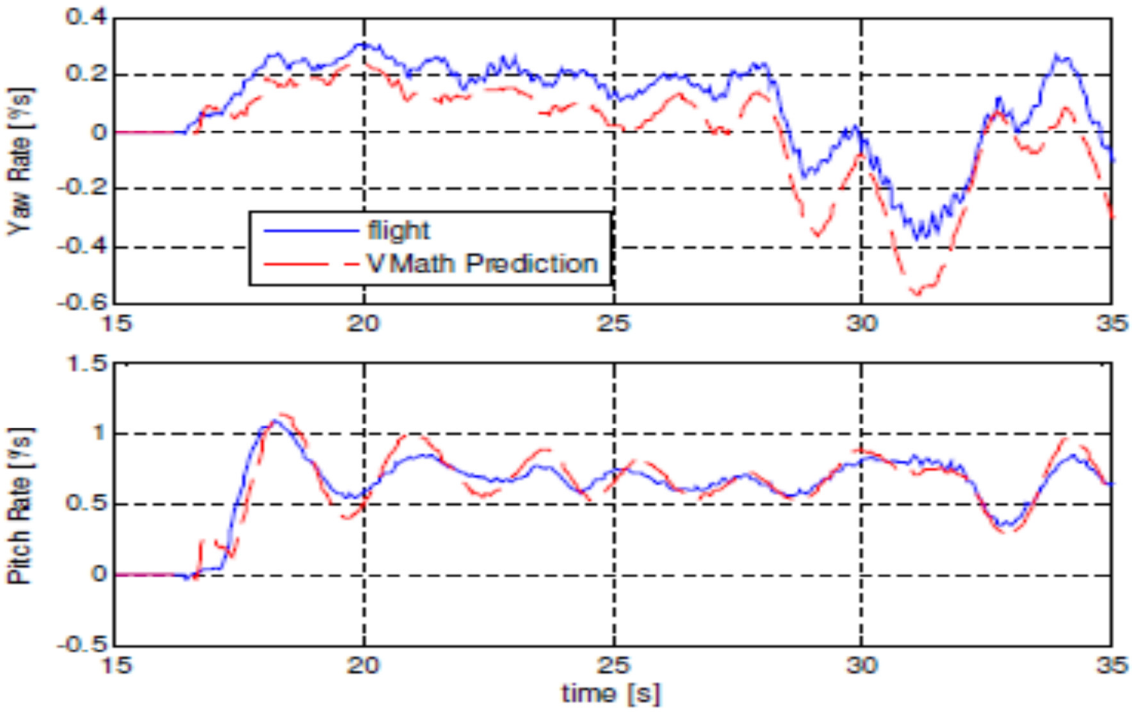

Figure 1: Comparison between Flight data and simulated reconstruction

This oscillation has been naturally associated to the first bending mode. The duration of first stage flight is about 110 s. The oscillations are visible during several bursts specially around 30 s.

The simulation with 6DOF simulator VEGAMATH does not capture the amplitude of the oscillation seen in flight (up to 0.1 deg/s). This paper is aimed at finding an explanation of the discrepancy.

Note : the angular rate sent by Telemetry is computed by GNC basing on attitude angles issued by INS (even if available in INS, the angular rates are not direct GNC inputs but computed inside the GNC algorithms). The computation of angular rate uses the quaternion and the derivative of the quaternion. The derivative is obtained by a filter to limit the noise : as a consequence the level of the 4 Hz component in the observation is lower than the one expected on the actual rate sensed at INS. It means that for 0.1 deg/s observed on estimated angular rate, we must expect 0.2 deg/s on real angular rate, making the discrepancy between flight data and simulated data higher.

2.4 Other modal observations

The 1st mode at 4hz on PQR is also observed on the LINS measurement. The variation of the frequency versus time is as expected. Thanks to the higher bandwidth of the measurements, upper modes are also observed. The analysis in the bandwidth around 4 Hz show the same evolution as for INS measurement. The only difference is the level of amplitude which is compatible with the values of the estimated shape slope respectively at INS location (upper module) and at LINS location (inter-stage 1 / 2). The amplitude of modal contribution on estimated angular rate is of 0.1 deg/s at 30 s and 40 s.

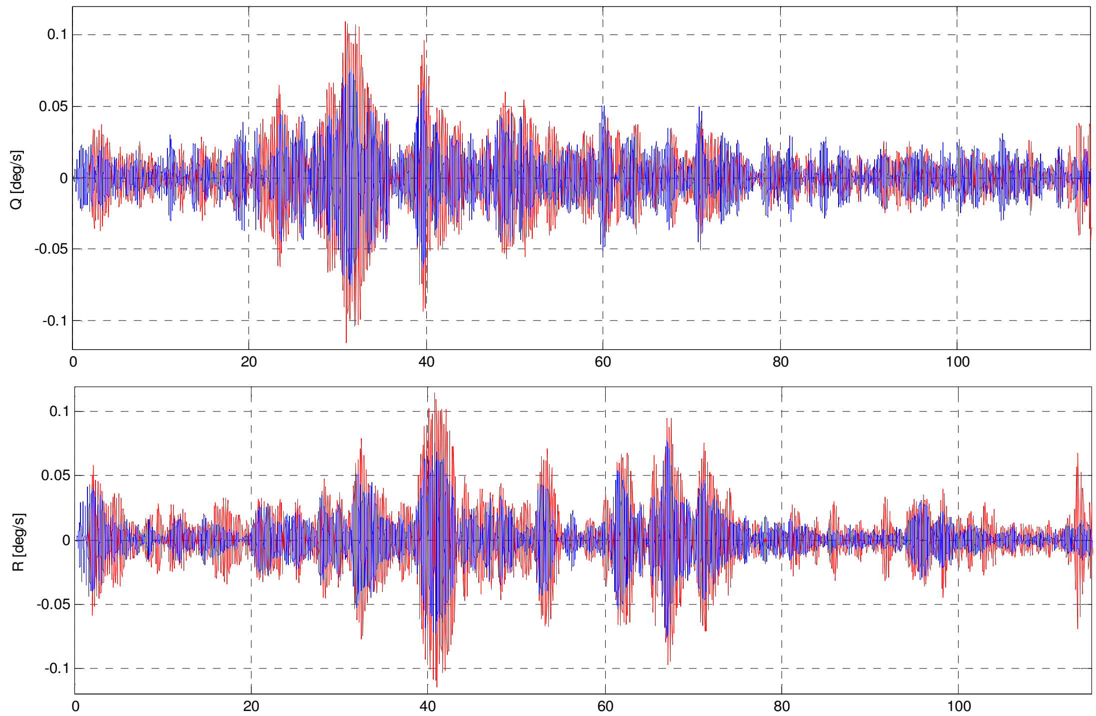

Figure 2: Signal in 4 Hz bandwidth (red: INS measurement; blue: LINS measurement)

Basing on accelerations measurements, the ELV-AVIO Structure team has performed a modal identification of both frequencies and shapes. The approaches used are LSCE (Least Square Complex Exponential) and Poly-Reference. The evolution of frequencies of modes 1, 2 and 3 versus flight time is given in the Figure 3 and is aligned with prediction. The first mode frequency is the same observed on angular rate and comforts the assumption.

2.5 Other variables

The analysis of the TVC commanded deflection (through FFT) does not evidence component at 4 Hz.

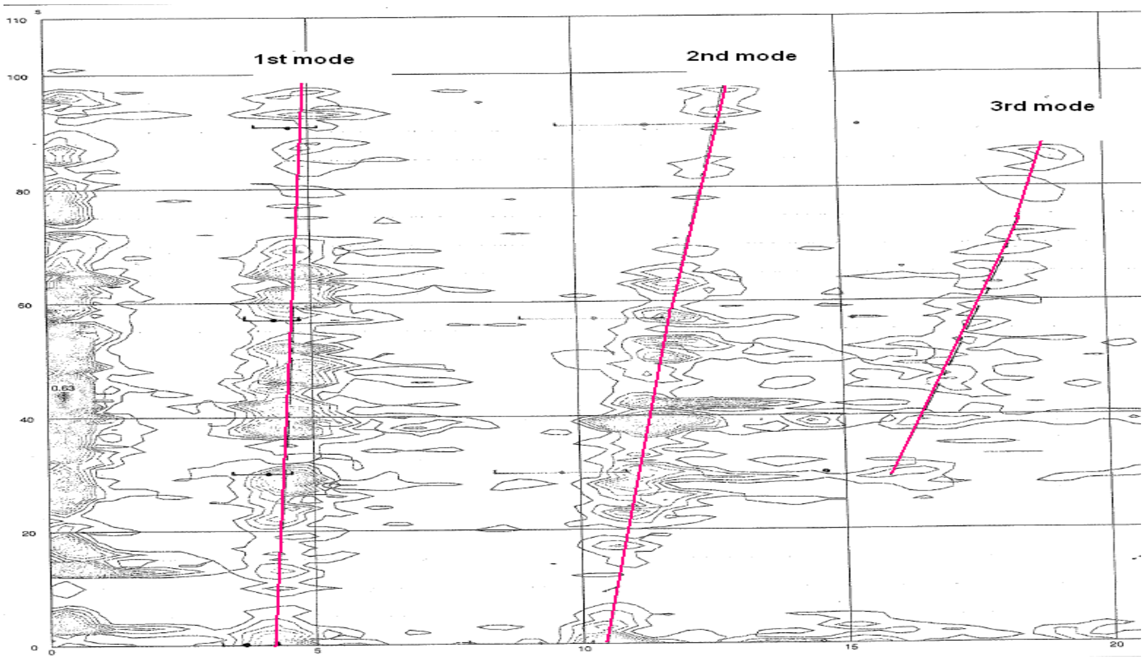

Figure 3: Identified elastic modes (abscissa: Hz; ordinate: flight time) based on accelerometers

3. TVC Control in atmospheric flight

3.1 Architecture

The TVC Control algorithms implemented in VEGA FPS are quite classical (see for instance [2]) and are briefly summarized. A main design assumption is that the launcher is axial symmetrical and that the two channels (pitch and yaw) can be controlled separately basing on SISO approach.

The digital controller works at 25 Hz (40 ms).

The TVC deflection law is the sum of:

- signal using attitude error (Proportional and Derivative terms)
- signal using drift velocity wrt reference trajectory (Proportional and Integral terms)

The attitude errors (with respect to pre-programmed pitch and yaw profiles) and the drift velocities are issued by the Guidance function.

3.2 Tuning

The gains are scheduled versus velocity to cope with varying parameters conditions of the flight phase (Mach number, dynamic pressure, thrust). An example of evolution of dynamic pressure, Mach number and velocity for LARES mission is given on the Figure 4. The remarkable instants are 31 s (transonic) and 55 s (maximal dynamic pressure).

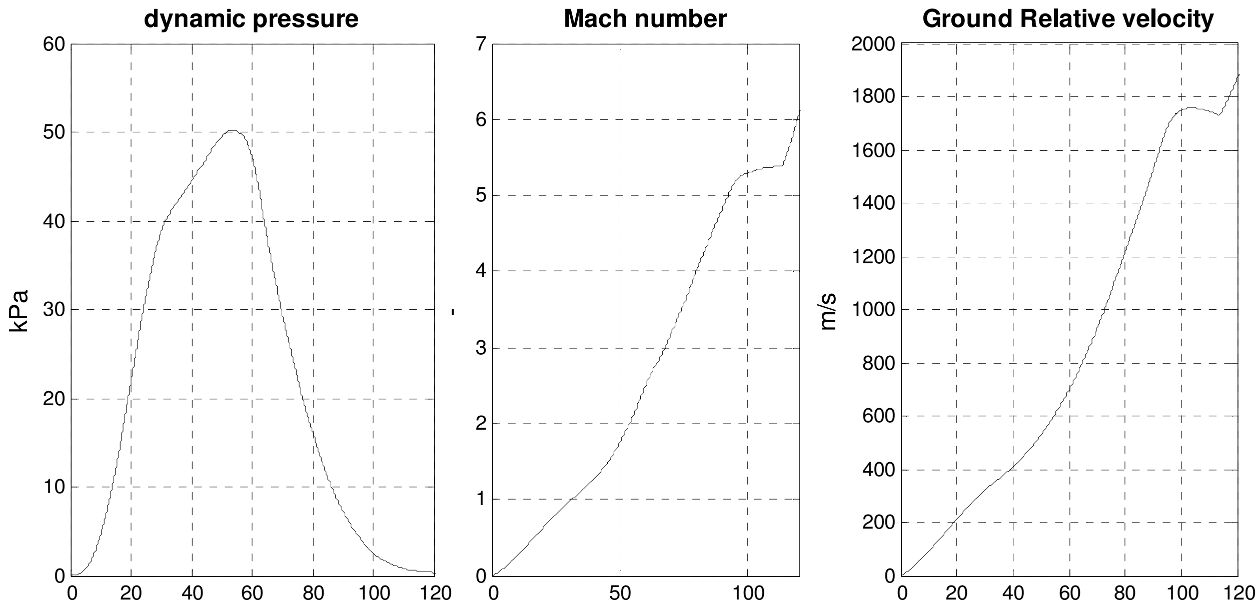

Figure 4: Trajectory variables for LARES mission

The rigid frequency in closed loop is around 0.2 – 0.5 Hz.

Several filters are added in the control loop to notch the bending modes and to retrieve rigid margins around the rigid closed loop frequency.

The first bending mode located around 4 Hz, is phase-controlled: this solution is preferred since the filtering action consumes less phase than a gain controlled approach. Another advantage is the robustness to the modal damping uncertainty. The counterpart is that the modal frequency is to be known with sufficient accuracy. It also means that the bending mode behaviour is sensible to any additional delay in the chain.

The upper modes are gain controlled because there a more uncertainties on their characteristics. In addition the sampling frequency of 25 Hz creates aliasing around 12.5 Hz which mixes the spectrum above 6 – 7 Hz. Anti-aliasing filters are also present. The modal peaks are not clearly distinguished.

The modal data are predicted basing on a 3 dimensional FEM model of the launcher. The modes are time varying in function of propellant consumption. The bending modes also depend on the upper part of the launcher i.e on the payload mass characteristics: they are mission dependant. As a consequence, if the uncertainty of the modal frequency is not too high, a unique tuning can cover a range of payload masses. On the contrary if the uncertainty is high, the tuning (basically the notch filter) is specific to the mission.

3.3 Validation

The validation is based on

- frequency domain analysis (Nichols plots for each channel) where the stability margins are read (low frequency gain margin, rigid phase margin or equivalently delay margin, high frequency rigid gain margin, 1st mode phase margin, upper modes gain margin)
- time domain analysis (6 DOF nonlinear simulations).

4. Identification by internal parameters: delay, modal data, actuator nonlinearity

4.1 Delay effect

The increase of oscillations can be created by a delay in the loop higher than the predicted one. To increase significantly the amplitude of the 4Hz oscillation, a high delay should be added in the chain. In this hypothesis, the rigid mode should be affected before the 4Hz bending mode i.e we should have also important oscillation at low frequency 0.5 Hz.

This has not been observed and so this explanation should be discarded.

4.2 Modal shape

The increase of oscillations can also be created by a modal shape at INS higher than the predicted one.

The simulations show that to reproduce the level observed in flight:

- the shape at INS should be twice the value retained as nominal which is outside the foreseen scattering,
- with an increase of the delay in the control loop.

This explanation is not probable since the post-flight analysis performed by ELV-AVIO Structure team (referred supra in paragraph 2.4) shows that the reconstructed modal data are slightly lower than the predicted ones (iand not twice the predicted value!).

4.3 Modal frequency

The post-flight analysis performed by ELV-AVIO Structure team also evidences a slight discrepancy in the frequencies: the first mode is 8% higher than the prediction (in any case still in the foreseen range). Even if the notch filter is centred on the nominal 1st mode frequency, it is large enough to cover a range of uncertainty.

This slight shift of frequency cannot explain the amplitude of oscillations.

4.4 Modal damping

The increase of oscillations can also be created by a damping less than the predicted one. The simulations show that to produce amplitudes compatible with the observations, the modal damping ξ must be set to zero. Is it compatible with physical data?

The predicted structural damping have been assessed both from computations (combining the damping estimated on each element) and from tests on mock up (based on logarithmic decrement approach). The structural damping has been estimated at 0. 8% for the 1st bending mode.

In flight the damping is modified by two effects:

- Aero-elasticity: it can be shown that the coupling between distributed aerodynamic and elasticity increase the damping of the 1st bending mode (see for instance [4])
- Closed loop: the TVC control loop modifies the poles and in particular the 1st bending mode. We have computed that the contribution of the closed loop on the modal damping is of about +2%

In conclusion, it is not possible to explain the amplitude of the oscillations by a damping lower than predicted.

4.5 Actuator backlash

The TVC actuators of VEGA for all stages are Electro-Mechanical Actuators (EMA) designed by SABCA. From TVC control point of view, they are characterized by

- a transfer function in linear zone,
- saturations in deflection and deflection rate,

- low amplitude nonlinearities (backlash).

The oscillations of 1st bending mode could be created by a limit cycle caused by backlash.

This cause has been discarded: the backlash is responsible of the limit cycle on the rigid mode (0.5 Hz) but not on the 1st bending mode. In effect, a limit cycle has been observed in 1st stage tail off as well as on upper stage. The phenomenon has been explained by describing function approach (see [3]) following the successive block transformations shown in Figure 5.

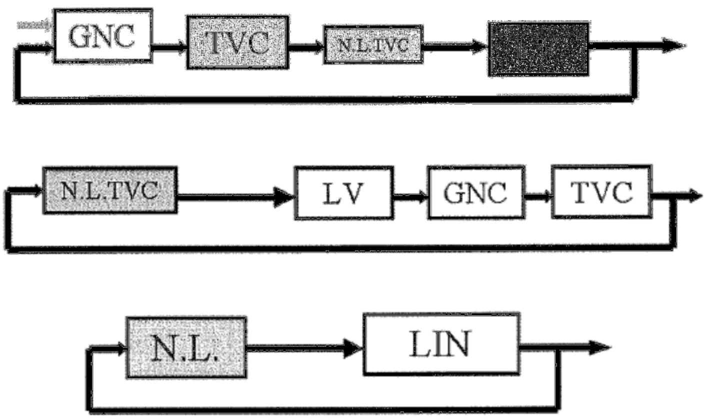

Figure 5: Transformations to be in standard describing function formulation

It is thus equivalent to plot the classical Nichols plot of the TVC Control loop, in closed loop open at the input of the TVC as well as the nonlinear locus of the backlash (graduated in amplitude), as reported on the Figure 6. We notice that an intersection between the linear locus and the nonlinear locus occurs at the frequency of the rigid mode (0.5 Hz = 3 rad/s). There is no intersection of the nonlinear locus with the resonance of the 1st bending mode (4 Hz = 25 rad/s) and so no risk of limit cycle at 4 Hz.

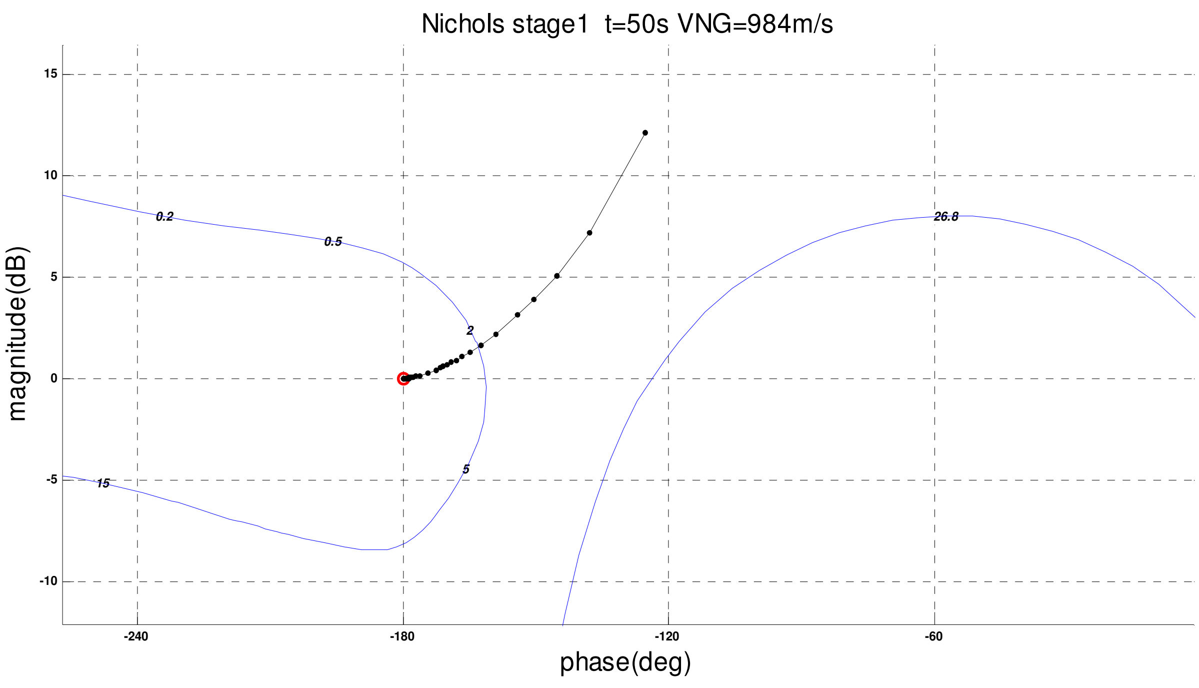

Figure 6: Nichols plot of the linear part and of the nonlinear part (backlash)

5. Identification by external signal: wind

Since it was not possible to explain the oscillation by identification of internal parameters, the source has been searched in external forcing terms. The fact that component at 4Hz was not found in the TVC deflection angles also confirmed that the stability loop was not involved in the phenomenon.

The wind is the main external disturbance in atmospheric flight.

5.1 Aero-elastic Model

The model involves a set of aero-elastic integrals which shows the coupling between elastic modes and aerodynamics distributed along the launcher. The aero-elasticity couples the different LV variables: the rigid drift velocity Z', the rigid rotation Ψ and the bending modes. The full model of LV is analysed in terms of internal stability in presence of sensors, TVC actuators and Control Loop.

The aero-elasticity has been shown to increase the rigid instability coefficient A6 and to increase the damping of the bending modes.
The mode can be also excited by a direct forcing term due to wind as evidenced in the following motion equation of the mode q:

$$\ddot{q} + 2 \cdot \xi \cdot \omega \cdot \dot{q} + \omega^2 \cdot q = pdyn \cdot Sref \cdot \int_0^L \Phi(x) \cdot C_{N\alpha}(x) . \frac{W(x)}{Vrel} \cdot dx \quad . \tag{1}$$

We remind that generalized mass is normalized to 1 and does not appear in the equation.

The modal shape Φ(x) is function of the abscissa along the launcher as well as the lift gradient $CN\alpha(x)$.

The wind velocity *W* is:

- the horizontal component projected on yaw direction for bending mode associated to yaw,
- the projection of horizontal component in the plane orthogonal to the LV longitudinal axis for bending mode associated to pitch. It means that the flight path angle is involved in the transformation.

The launcher has a length of 30 m. We only consider wavelength higher than 50 m since the characteristics length associated to a frequency 4 Hz for a velocity of 300 m/s (reached before 30s) is 75 m. In this case the wind can be assumed to be constant over the whole launcher. The equation reduces to:

$$\ddot{q} + 2 \cdot \xi \cdot \omega \cdot \dot{q} + \omega^2 \cdot q = pdyn \cdot Sref \cdot \frac{W}{Vrel} \cdot \int_0^L \Phi(x) \cdot C_{N\alpha}(x) \cdot dx \tag{2}$$

We define the integral aero-elastic:

$$CN_{\alpha\Phi} = \int_0^L \Phi(x) \cdot C_{N\alpha}(x) \cdot dx \tag{3}$$

The aero-elastic coefficient $CN_{\alpha\phi}$ is obtained by integrating the lift distribution and the modal shape. The numerical evaluation is a function of Mach (for aerodynamic) and time (for shapes). The order of magnitude of the coefficient is between 0.02 and 0.03. An evolution versus time is given in the Figure 7. We observe an important increase at the transonic instant due to the change of aerodynamic coefficient when Mach is close to 1. It means that we may expect an increased excitation close to transonic instant (30 s).

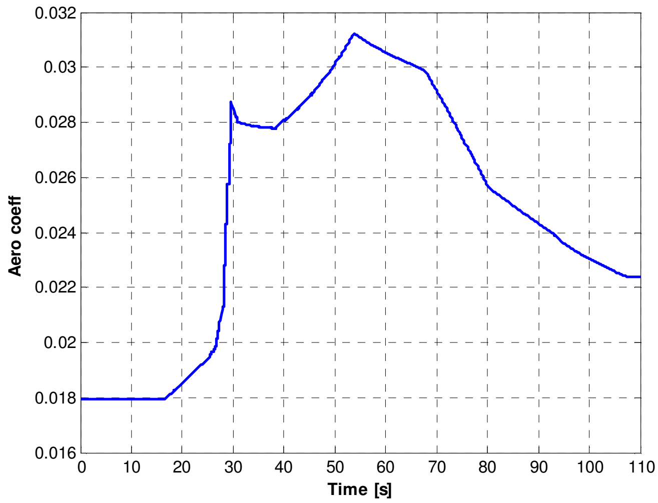

Figure 7: Aeroelastic coefficient $CN_{\alpha\phi}$ versus flight time

The other parameters involved in the formula and function of time are the dynamic pressure and the relative velocity. It is important to notice that the ratio pdyn / Vrel has a different profile than the dynamic pressure. While the dynamic pressure has a peak around 55s, the ratio pdyn / Vrel has a peak around 30s. It means that the maximal effect of a wind disturbance on the mode is expected at 30s which is actually observed in flight.

5.2 Real Winds Model

Real winds database (collected daily for Kourou CSG and described in [5]) is a set of winds profiles (components North-South and East-West) versus altitude composed by:

- a quasi-static component, obtained through the measurement of winds at different altitudes, up to 20km, at different hours of the day and different days of the year,
- a distribution of high frequency profiles, having a wavelength between 50m and 2000m, called meso-scale component. This component is characterized statistically by a power law spectrum of slope -3 versus spatial frequency (or equivalently a law with slope +3 versus wavelength).

This last component is able to act as an external input on the flexible modes of the launcher, being the relative velocity of the launcher included between 200m/s and 1000m/s in the interval 20s-70s, so that the corresponding limit frequencies for a wavelength of 50m are within 4 and 20Hz and for a wavelength of 1000m are within 0.2 and 1Hz.

In the Figure 8, are presented the wavelength corresponding to a frequency of 4Hz versus flight time. We confirm that the wavelengths between 50 m and 2000 m can interact with the mode. The next plot is the DSP (Power Spectral Density) with a power law in +3: the amplitude of statistical wind increases with time. The last plot is the ratio pdyn / Vrel with a peak at 30s.

There is another statistical component (called Turbulent) concerning wavelength less than 50 m and characterized by a power law spectrum with slope -5/3. It is not modelled in real winds database. For GNC studies it corresponds to frequencies higher than (and thus on interacting with) the first bending mode.

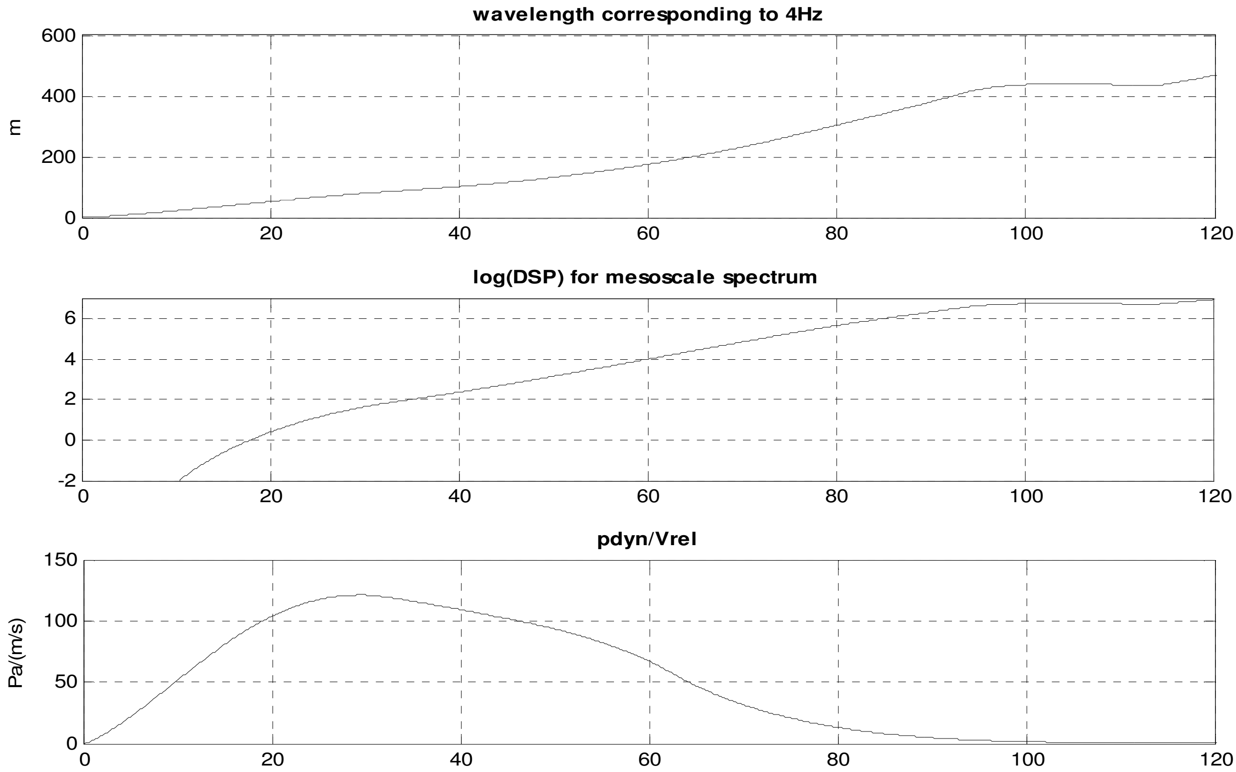

Figure 8 : wavelength, DPS and efficiency of wind

5.3 Simulation Results in case of aero-elasticity

Applying a real wind extracted from the database on a launcher model in which the aero-elastic forcing term is included, the first mode can be excited inducing oscillations of the same order of magnitude of those seen in VV01 flight, without having the need of adding a large scattering in terms of delay of control loop, or bending mode deviations with respect to those foreseen by FEM model and confirmed by ELV-AVIO structure team post-flight analyses.

The evolution of the elastic component of angular rate at INS level is depicted in Figure 9. Angular rate observed in flight telemetry is computed through the derivative of the filtered Euler angles provided by the INS. The result of this filtered estimation is a decrease of the amplitude of the real elastic oscillations of a factor greater than 2. In Figure 10 the estimated angular rate provided by the on board computer (red curve) is compared to the real one (blue curve). Maximum estimated oscillations have an amplitude of about 0.1°/s, a level completely in line with what experienced during VV01 flight (see Figure 2).

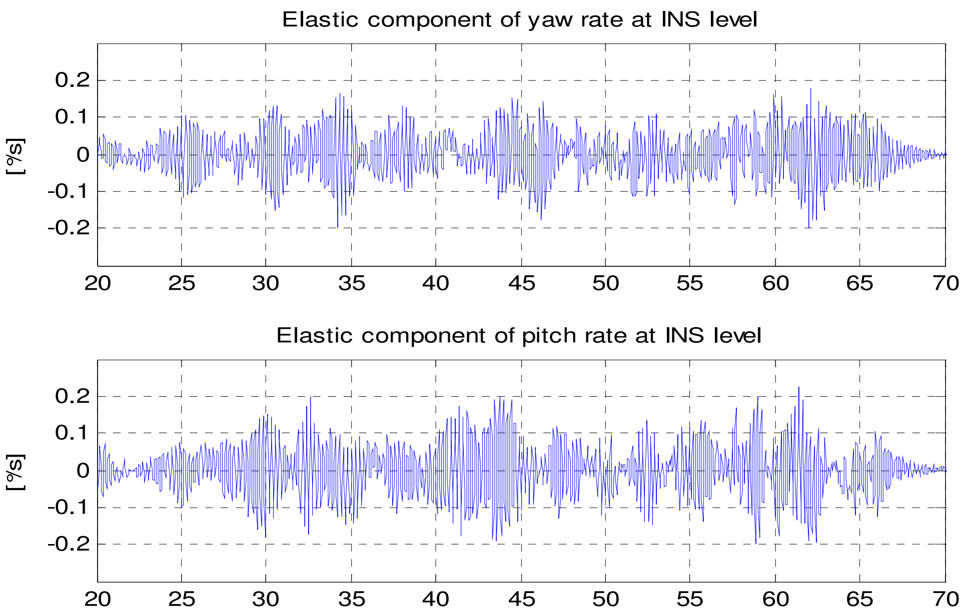

Figure 9: Elastic component of yaw and pitch rate at INS level

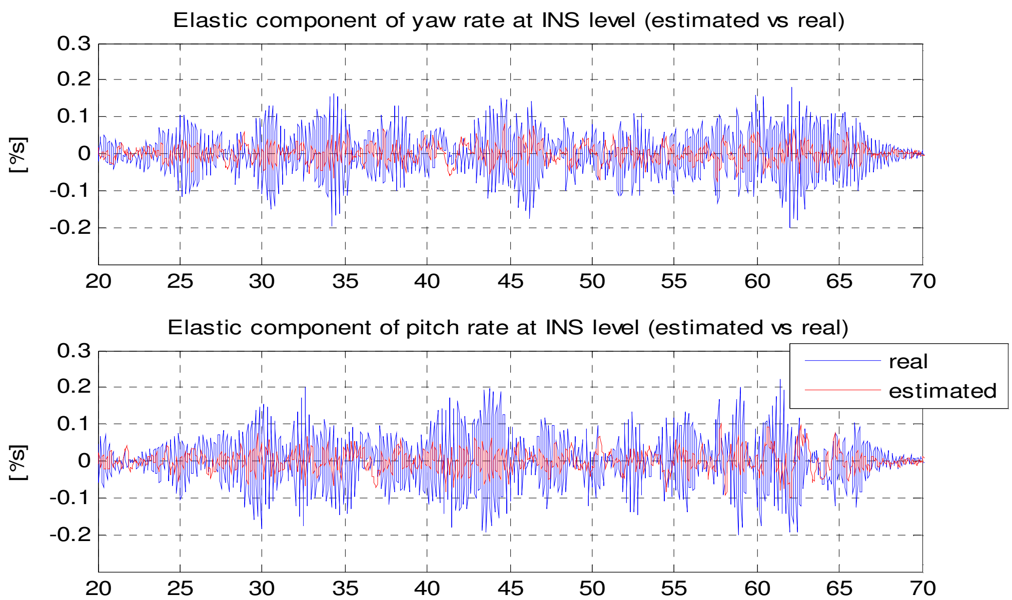

Figure 10: Real vs estimated elastic component of yaw and pitch rate at INS level

A comparison of the angular rates seen in flight VV01 and those obtained through the simulation including aero-elasticity is presented in Figure 11, with a zoom of the interval 25-35s.

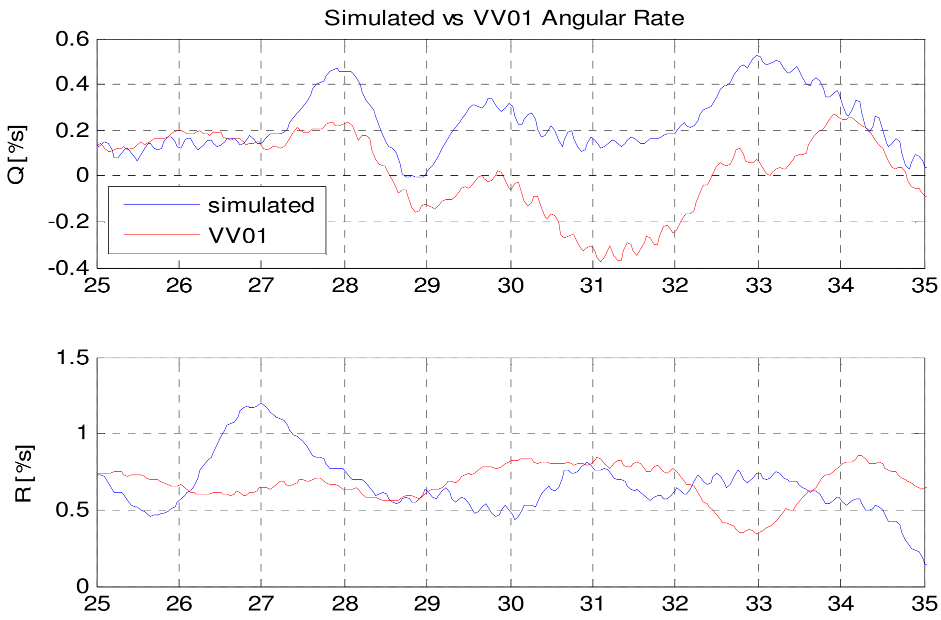

Figure 11: VV01 and simulated yaw and pitch rate from on board estimation (telemetry data)

Note 1: when using the sounding wind, it is not possible to fit perfectly the low frequency component: the sounding is done exactly at the instant of flight but several hours before or after. A better fitting can be obtained by reconstructing also the wind profile (low frequency component) using a Kalman filter. Such a tool has been implemented in ELV.

Note 2: these analyses have been confirmed by specific study in which each wind component (only low frequency part, only meso-scale component; individual sines at different frequencies) has been put through the system and the responses analysed.

5. Conclusion

The scope of the post-flight analysis is as far as possible to explain the various phenomena encountered in flight and to reproduce in simulation the evolution of the flight variables.

The oscillation of the first bending mode at 4Hz is not at first sight an important phenomenon: it is seen on transversal rate in several bursts and at moderate amplitude (0.1 deg/s).

Nevertheless the fact that on the simulations in flight conditions (with reconstructed masses, propulsion, elastic modes, actuators and sounding winds) the first bending mode was at amplitude lower than in measurement had to be explained.

An inconsistency in launch data (modal characteristics, actuator characteristics) could be feared. Since the stability of the TVC Control loop is highly dependent on these parameters (in particular being the first bending mode controlled in phase), it was important to understand if the announced stability margins were the real ones.

Several root causes were envisaged to explain the amplitude (delay in the loop higher than foreseen, modal shapes higher than predicted, modal damping very low, backlash in actuators, combination of these different causes). Each of these causes has been discarded (deemed unrealistic or even impossible).

The most natural explanation is found in the meso-scale component of the wind. The sounding wind does not include this component (wavelength in the range 50 m – 2000 m) for simple sampling reasons. On the contrary the so-called “real winds” (available in the Kourou database and used for launcher qualification) do include this component. Since not directly observable on sounding but nevertheless present in the atmosphere, the meso-scale component is mathematically generated basing on a given spectrum and superimposed on the measured profile. This provides more realistic winds for simulation of the elastic modes in presence of aero-elastic terms and allows reproducing the oscillation at 4Hz and 0.1 deg/s of amplitude observed during VV01 LARES on estimated angular rate (corresponding to 0.2 deg/s on real angular rate).

After the success of VV02 PROBA V flight on May 7th 2013, the second post flight analysis for VEGA has been started. The same verification will be carried out on the angular rate measurements. At the moment (end of May), the analysis is going on.

Acronyms

CSG = Centre Spatial Guyanais
DOF = Degree Of Freedom
EMA = Electro Mechanical Actuator
FEM = Finite Element Model
FPS = Flight Program Software
GNC = Guidance Navigation and Control
INS = Inertial Navigation System
LSCE = Least Square Complex Exponential
SISO = Single Input Single Output
TVC = Thrust Vector Control

References

[1] Greensite, A.L. 1967. Analysis and Flight of Space Vehicle Flight Control Systems. Volume XV: Elastic Body Equations. NASA CR-834.

[2] Greensite, A.L. 1967. Analysis and Flight of Space Vehicle Flight Control Systems. Volume VII: Attitude Control During Launch. NASA CR-826.

[3] Gelb A. and W.E. Vandervelde. 1968. Multiple Input Describing Function and Nonlinear System Design, McGraw Hill.

[4] Orr, J.S. 2010. A Coupled Aero-elastic Model for Launch Vehicle Stability Analysis. In: *AIAA GNC Conference 2-5 August 2010, Toronto.*

[5] CNES. 2007. Environnement Naturel pour un Lanceur Spatial décollant du Centre Spatial Guyanais. Report LS-ST-1-X-0008-CNES.

[6] Effects of Structural Flexibility on Launch Vehicle Control Systems. 1970. NASA-SP-8036