LARGE DEBRIS DRAGGING AND DE-ORBITING BY VEGA LAUNCHER USING A TETHER

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ABSTRACT

Thanks to limited adaptations - additional propellant tanks, addition of a small probe, few SW and Guidance, Navigation and Control (GNC) modifications - the launcher VEGA can be shown to be suited in terms of performances, safety and costs to a de-orbiting mission. Such a mission consists of three main phases: rendezvous, capture and de-orbiting. Focused on the last phase, this work presents the adaptation of GNC algorithms to realize the de-orbiting of a debris dragged by VEGA by means of a tether.

1 INTRODUCTION

The de-orbiting mission is naturally divided in three phases:

- a quick rendezvous after a phasing in intermediate parking orbit (300 km),
- a closing and capturing phase thanks to a probe equipped with a tether of about 1 km length (at the moment the grabbing concept can be left still open: wire, net, harpoon, arm...). The launcher VEGA is in a waiting phase at a safe distance,
- finally, the dragging and direct and immediate de-orbiting of the space debris trailed by the launcher.

This last phase is characterized by the following features:

- two bodies in orbit linked by a tether, with residual motion,
- launcher acceleration given by the liquid propulsion system of VEGA: thrust of 2400 N applied on higher mass (e.g. 2000 kg of VEGA + 8000 kg of space debris). It implies that the de-orbiting, though much quicker than if performed by electric propulsion is slower than a typical VEGA de-orbiting: typically 1000 s instead of 100 s.

The paper is focused on this last phase and on the Control and Guidance aspects. The Navigation is assumed to be based on Inertial Reference System (IRS) and GNSS hybridization, foreseen in the frame of VERTA program with ESA.

The map is as follows:

- remind the baseline VEGA missions and launcher characteristics,
- summarize a debris de-orbiting mission by VEGA,
- remind the GNC algorithms used in VEGA for orbital phase and last stage de-orbiting. We clearly evidence the weak points of the baseline algorithms for the debris application:
    - o disturbance of the pendular motions (which can be seen as a “giant sloshing”) on Control and Guidance,
    - o lack of precision of a (Quasi) Open Loop Guidance for a phase of such duration and for a challenging target (re-entry in Ocean),
- improve the GNC algorithms to cope with debris de-orbiting needs:
    - o a Closed Loop Guidance scheme to target an impact point in the Ocean with sufficient accuracy,
    - o additional feedback variables to perform the Control (in particular the use of the relative state Launcher – Debris to improve the control),
- present a mechanical model of the two bodies system linked by a tether. Different phenomena are included: attitude dynamics of the launcher, orbital libration, different pendulum motions associated to the tether, elasticity of the tether, possibility of having time intervals with no tension of the tether. This model is used to validate the concepts in time domain and frequency domain (for the linearized model).

2 VEGA LAUNCHER: BASELINE MISSIONS

2.1 First and second Missions

The VEGA launcher is the new small and versatile European Launcher under ESA contract. The successful maiden flight of February 13th 2012 has released from French Guyana Space Centre the LARES 400 kg satellite on a circular orbit of 1500 km. The second flight foreseen on April 2013 will release successively

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PROBA-V on a Sun Synchronous Orbit (SSO) at 820 km and VNREDSAT on a SSO at 669 km.

2.2 Baseline Missions

The launcher is designed to perform a set of different types of missions, with wide flexibility, thanks to a liquid propellant upper stage which can be ignited up to 5 times:

- typically single Payloads (PL) missions with two boosts for reaching a circular orbit and a deorbiting boost,
- as well as multi PL missions with two additional boosts for the release of an additional PL.

The targeted missions are Low Earth Orbits (LEO) from 700 km to 1500 km and for PL masses ranging from 300 kg to about 2000 kg. The orbits are of various types: equatorial, polar, SSO. The reference mission puts in orbit of 1500 kg at 700 km.

2.3 Architecture

The launcher is comprised of three solid rocket motor stages (P80, Z23 and Z9) and of an upper stage AVUM with liquid propellant motor. All the four stages are controlled thanks to an electric Thrust Vector Control (TVC) System. The upper stages is also equipped with a Roll and Attitude Control System (RACS) composed of two clusters of three thrusters of about 240 N each, based on mono-propellant (hydrazine) blow down system. It allows the roll control in boosted phase and three-axes control in ballistic phase.

3 VEGA LAUNCHER: DE-ORBITING MISSIONS

3.1 Complementary Propulsion

The launcher in its baseline configuration is not able to perform the direct de-orbiting of a body of several tons in LEO (see [1]). Two solutions are possible: either to embark on the launcher a dedicated module with a proper propulsion system in charge of performing the deorbiting, or to complement the AVUM LPS (Liquid Propulsion System) by additional tanks while keeping the same liquid propulsion system. The second solution is considered in this concept since it leads to save development time of an already qualified motor and since it allows a propulsion system with sufficient acceleration (higher than with concepts such as electric propulsion).

3.2 Quick Rendezvous

The rendezvous to the debris is performed thanks to the four available AVUM boosts. Two boosts are used to reach a parking circular orbit at about 300 km of altitude. Two other boosts are aimed at reaching the debris neighbourhood on a circular orbit at 800 km of altitude (see for instance [2]). For safety reasons the AVUM is kept at a distance of 1 km from the debris in a stable orbital relative configuration.

3.3 Debris Capture by a Probe and a Tether

The closing is not performed by the AVUM but by a small probe equipped with specific propulsion and sensors (LIDAR, Cameras) and linked to the AVUM by a tether. The probe is in charge of closing the debris, and attaching the tether to it. The close operations can be performed in two ways, both by means of proximity sensors: either to automatic and self-governing performance or thanks to tele-operation from Ground. The two options are possible and have pro and cons. The device used for attachment (node, harpoon, net…) is not object of the present paper.

3.4 De-orbiting by Dragging

Once the debris has been linked to the AVUM by the probe, the AVUM can start the de-orbiting phase. The de-orbiting ignition is commanded, the tether is tensed and the AVUM starts dragging the debris in a stable configuration. The boost is optimized to allow a direct re-entry of the two bodies and an impact inside the Ocean.

3.5 This concept inside the literature

The use of VEGA as candidate is found in literature (see for instance [3] and [4]). The use of a tether to drag a debris is referred in several papers (see [5], [6]). In the so-called “Capture technologies at middle distance” the flexible tether is advocated since it “allows not considering Centre of Gravity (COG) alignment with thrust axis as a constraint as for any rigid link solution”. The counterpart is to have suited GNC algorithms.

4 GNC: BASELINE CONFIGURATION

4.1 Sensors

The only sensor is a IRS without redundancy.

4.2 Navigation

The Navigation is in charge of:

- integrating the IRS outputs to estimate the launcher position and velocity in an inertial reference frame,
- passing the attitude quaternion from IRS to Guidance,
- estimating the acceleration to decide the instants of separation ATD (Acceleration Threshold Detection),
- estimating the drift and drift velocity by

integration of non-gravitational acceleration in reference trajectory frame.

4.3 Guidance

The Guidance is twofold:

- Closed loop Guidance (CLG) during the boost 1 and 2. The target is the transfer orbit during the 1st boost and the final orbit during the 2nd boost. The algorithm is based on linear tangent law with final conditions on velocity and position, which is updated every Guidance cycle (1.28 s),
- Open Loop Guidance (OLG) during the boosts 3, 4 and 5. With the current IRS, the accuracy of the Navigation is not sufficient to permit a CLG scheme during the successive boosts. That is why a OLG scheme (predefined linear law of pitch and yaw) is envisaged. In any case it is not a full open loop: the Navigation is used to trigger the ignition (via angular range condition) and the cut-off (via a delta velocity condition) of the motor.

The de-orbiting boost commanded by OLG nevertheless ensures a compliant re-entry footprint submitted to Safety authorities (see for instance VEGA 2nd flight mission analysis review and [7]). The footprint dimension is function of:

- initial state errors (which could be reduced by Navigation improvement),
- fragmentation scenario which induces a domain of DV and ballistic parameter (see for instance fragmentation and re-entry model described in [8]),
- atmospheric characteristics.

Orders of magnitude (coming from PROBA-V mission definition) are as follows: the AVUM re-entry footprint has a longitudinal extension of about 1000 km (lateral extension is very inferior). The re-entry (drag end explosion effect) contribution is off 600 km while the influence of initial conditions is of 400 km.

4.4 TVC Control

Thanks to axial symmetry of the launcher, the control channels in pitch and yaw are decoupled and commanded separately. The coupling between the channels in presence of roll rate is taken into account in the design of the law.

The objective of TVC control is manifold:

- control of attitude (pitch and yaw) via a Proportional Derivative controller (PD): gains Kp and Kd,
- integral control for attitude in case of CLG (to compensate offset of COG),
- control of trajectory in case of OLG via the variables of drift and drift velocity (gains Kz, Kzd),
- notching and/or phasing the sloshing modes if any (in particular of the PL).

As an example, the tuning for de-orbiting phase in the baseline configuration is:

- $Kp = 1.76$
- $Kd = 1.425$
- $Kz = 0.004$
- $Kzd = 0.064$

4.5 ACS Control

The ACS control through two clusters of three thrusters is based on a linear PD implemented through a Pulse Width Modulation (PWM) since the command of thrusters is ON/OFF.

The proportional law is based on quaternion feedback and the derivative part on angular rate in body axes ([9],[10]).

5 GNC: ADAPTATION FOR DE-ORBITING MISSIONS

5.1 Hybridization INS / GNSS

The hybridization can be made outside the VEGA FPS (Flight Program Software): in this case the current interfaces can be kept as is. It is the same upgrade as replacing the sensor by another one more accurate.

This activity is foreseen in the frame of VEGA accompaniment ESA contracts (VERTA).

A second IRS could be added to ensure sufficient reliability for such a mission if needed.

5.2 Modification of Control: additional feedback

The feedback law of the basic configuration (PD in attitude error and PD in drift displacement) is completed by a PD in angular position of the debris with respect to the launcher (equivalent to relative position).

This angular position is obtained with a sufficient precision for this purpose from:

- the absolute position of the launcher provided by hybrid Navigation,
- the absolute position of the debris transmitted by the probe in charge of the capture. The probe is assumed to be also equipped by a GNSS.

This additional feedback permits to keep the two bodies (prey and chaser) align along the path.

A simple control law can be obtained by

LinearQuadratic Regulator (LQR) techniques basing on a linearized model (described infra).

The residual rotational motion of the debris is not controllable and is considered as a disturbance.

5.3 Modification of Guidance: Tether tension

The tension of the tether can be provided:

- either by AVUM propulsion. In this case, we should ensure that the discontinuity can be absorbed. The acceleration passes from 1 m/s^2 to 0.2 m/s^2. The flexibility of the tether acts as a longitudinal mode of the overall system,
- or by the RACS as a preliminary manoeuver. The behaviour can be smoother but it complicates the algorithms requiring good coordination.

5.4 Modification of Guidance: de-orbiting manoeuvre

The OLG scheme is not sufficient to ensure a good precision: the predicted DV computed on ground to ensure the de-orbiting might no more be suited to achieve re-entry accuracy.

A simple improvement of Flight Management can be done: the AVUM cut off instant is triggered basing on Instantaneous Impact Point (IIP) computation. This point is obtained by formula in ballistic conditions (e.g. down to altitude 120 km) and by atmospheric correction accounting for drag coefficient (e.g. based on table to cope with real time constraint). By doing so it is not necessary to implement in the Guidance a propagation of the thrust effect (as done for instance in CLG). It is sufficient to compute at each instant the impact assuming the thrust is stopped immediately.

The admissible re-entry zone is assumed to be studied on ground and translated in an admissible ground track parameterized by an interval of latitudes (since the lateral extension of the footprint is negligible with respect to the longitudinal one).

This scheme can be refined by adding also a condition for AVUM ignition: instead of basing it on range condition, it can be based on IIP condition. This additional degree of freedom will allow to anticipate or delay the ignition to fulfil the re-entry footprint constraints.

The tether will be cut at the end of the AVUM cut off to avoid orbital disturbances on the two tethered bodies: in absence of propulsive acceleration the stable configuration will be along the vertical due to the gradient of gravity. Uncontrolled rupture of the tethered could lead to a moment exchange and unfortunately a re-orbiting of one of the bodies.

In a baseline mission as reminded in §2.2, the contribution of kinematical conditionsat cut off, which can be reduced by the algorithms, is about half of the footprint. Nevertheless in the case of a debris de-orbiting, the contribution of the other effects (explosion and ballistic parameters) is probably increased: the debris itself may be a complex body including residual propellant (while AVUM depleted its residual energies after its cut-off). It will result in an important footprint in spite of Guidance improvements.

6 VALIDATION: MODEL AND SIMULATOR

6.1 Nonlinear plan model

The study is based on a non-linear model defined in the orbital plan. It is derived from Lagrange approach. The degrees of freedom (DOF) are:

- the two translations x, y of the launcher in this plan (along orbital velocity and along local vertical assuming a circular orbit),
- the rotation angle ψ of the launcher around its COG,
- the angular position θ of the debris wrt the launcher(i.e. tether absolute angle),
- the elongation ξ of the tether assumed to be flexible,
- the rotation angle α of the debris.

We use the following notations:

- L is the nominal length of the tether,
- l_1 is the distance between launcher COG and the tether attachment point (which is also close to the thrust pivot point),
- l_2 is the distance between debris COG and the tether attachment point,
- m_1 and m_2 are respectively the launcher and debris masses,
- J_1 and J_2 are respectively the launcher and debris inertias at the attachment point,
- F is the thrust module.

The launcher is submitted to a constant thrust and thus to a quasi-constant acceleration. The two bodies system behaves as a pendulum, formally like a giant sloshing mode.

The lateral vibrations of tether seen as “taut string” are not taken into account in this model (see for instance [11], [12]).

The flexible modes of the two bodies are not taken into account. It is justified for AVUM whose first bending mode is above 30Hz. For the debris it depends on the possible appendices (solar panels…) and a verification will have to made a posteriori.

The libration mode due to orbital motion is also included, but is negligible wrt the launcher acceleration effect. This acceleration of about 0.2 m/s^{2}makes the motion simpler and the de-orbiting shorter. In absence of sufficient acceleration the two bodies system, aligned along the orbital velocity, would be an unstable configuration tending to reach a stable vertical configuration (dumbbell).

6.2 Linearized plan model

The linearized model is obtained by retaining the drift variable x and the rotation angles α, ψ, θ. The longitudinal displacement y is involved via the acceleration (i.e. the thrust) and is no more a variable. The elongation ξdecouples from the rest of the equations. We remind it is difficult to linearize the so-called "elastic pendulum" fundamentally non-linear (see [13] and [11]for instance). Nevertheless we will assume the control is not directly influenced by the longitudinal elastic motion and will verify the assumptions in final non-linear simulations.

The mass and stiffness matrices are given respectively in Equations (1) and (2).

$$\begin{bmatrix} m_1 + m_2 & m_2 \cdot l_1 & m_2 \cdot L & m_2 \cdot l_2 \\ m_2 \cdot l_1 & \dot{\smile}_1 & m_2 \cdot L \cdot l_1 & m_2 \cdot l_1 \cdot l_2 \\ m_2 \cdot L & m_2 \cdot L \cdot l_1 & m_2 \cdot L^2 & m_2 \cdot L \cdot l_2 \\ m_2 \cdot l_2 & m_2 \cdot l_1 \cdot l_2 & m_2 \cdot L \cdot l_2 & \dot{\smile}_2 \end{bmatrix} \quad (1)$$

$$\begin{bmatrix} 0 & F & 0 & 0 \\ 0 & \varepsilon \cdot l_1 & 0 & 0 \\ 0 & 0 & \varepsilon \cdot L & 0 \\ 0 & 0 & 0 & \varepsilon \cdot l_2 \end{bmatrix} \quad (2)$$

where

$$\dot{\smile}_1 = \dot{\smile}_{G,1} + m_2 \cdot l_1^2 \quad (3)$$

$$\dot{\smile}_2 = \dot{\smile}_{G,2} + m_2 \cdot l_2^2 \quad (4)$$

$$\varepsilon = \frac{m_2}{m_1 + m_2} \quad (5)$$

In open loop and in case the tether length L is high wrt launcher and debris lengths, we derive the approximated frequencies given in Equations (6) and (7).

$$\omega_1^2 = \frac{F \cdot \varepsilon \cdot l_1}{\dot{\smile}_{G,1}} \quad (6)$$

$$\omega_2^2 = \frac{F \cdot \varepsilon \cdot l_2}{\dot{\smile}_{G,2}} \quad (7)$$

Other frequencies are zero which is the consequence of a "free-free" configuration of the mechanical system (rigid translation and rotation) if we neglect the libration term.

The robustness of the law is not analysed in the frame of this preliminary study and the mass characteristics of the debris are assumed to be known with sufficient precision.

6.3 LQR control

A LQR controller is obtained from the linearized model. The debris rotational motion is practically not controllable: no weight are given on it and a null gain will result.

The weight matrices, based on physical considerations (0.1 rd for attitude angle, attitude rate and TVC deflection; 1 km for drift and 10 m/s for drift velocity) are defined in Equations (8) and (9).

$$Q = \mathrm{diag}\left(\begin{bmatrix} 10^{-6} & 10^{-2} & 0 & 0 \,.. \\ ..\, 10^{-4} & 10^{-2} & 0 & 0 \end{bmatrix}\right) \quad (8)$$

$$R = 10^{-2} \quad (9)$$

6.4 Full 6DOF nonlinear model

The full model is adapted to VEGA 6DOF simulators (VEGAMATH$^{©}$). The debris body is added with 6 DOF allowing rotational and translational motion. The addition of the elastic tether allows a simple interaction between the two bodies via the elastic force along the tether.

7 VALIDATION: OUTPUTS

7.1 Frequency Domain Analysis

The poles in open loop are for a debris of 8 tons respectively of 1 rd/s associated to VEGA rotational motion and 0.6 rd/s associated to debris rotational motion, in addition of two zeros as expected in free-free configuration.

The poles in closed loop with baseline controller are: -0.85 +/- 1.58i associated to VEGA motion, the pole unchanged at 0.6 rd/s of debris and two slow poles linked to trajectory: -0.0058 +/- 0.0174i and +0.0028 +/- 0.0167i, the latter being slightly instable.

The poles in closed loop with modified controller (exploiting debris position feedback) obtained by LQR approach are: -0.84 +/- 0.97i associated to VEGA motion and close to the one obtained by baseline controller; the pole unchanged at 0.6 rd/s of debris and two stable slow poles linked to trajectory: -0.0038 +/- 0.0033i and -0.0045 +/- 0.013i (corresponding to period of 7 min and 20 min respectively).

A Nichols plot corresponding to the LQR controller is provided in Fig.2. The two circles correspond to the open loop poles at 1 rd/s and 0.6 rd/s. Note: a damping has been added to help the readability of the plots. The low frequency gain reduction margin is due to the drift control.

7.2 Time Domain Analysis on plan model

The plan model has been simulated with the LQR controller in closed loop. Several initial conditions have been tried. A dynamics of second order and a saturation of actuator have also been introduced. Typical results are given on Fig 3. The tether tend to align ($\theta-\psi$ tends towards 0) while the debris oscillation α remain unchanged. The drift is also controlled.

8 CONCLUSION

8.1 Results

We have presented a simple adaptation of the current VEGA GNC architecture and algorithms to meet the requirements of a debris de-orbiting mission.

For Control we propose to add the feedback of the relative position of the debris (available via the probe sensors in charge of attach the tether). The control law obtained by LQR approach gives a closed loop behaviour close to a baseline mission (same orders of magnitude of gains) with an additional term controlling the position of the debris. The rotational motion of the debris remains as expected not controllable but stable.

For Guidance we propose a modification of the Flight management assuming a Navigation based on hybridization INS / GNSS: the AVUM cut off is no more triggered on a DV condition but on a nominal instantaneous impact point prediction. It will allow to reduce the contribution of initial conditions scattering. In any case the other contributions (DV of explosion and ballistic parameters of the debris) cannot be reduced and will produce a footprint with longitudinal expansion of more than 600 km. Such dimension is compatible with safety requirements encountered in VEGA baseline mission such as PROBA-V mission.

8.2 Work to be done

The dynamics model of the two bodies tethered system will be consolidated by showing that effects not taken into account are negligible (such as lateral vibrations) or can be treated separately (e.g. the introduction of artificial damping on the tether). Three dimensional effects will also be considered (mainly out of plane behaviour).

A complete simulation with all the modified GNC functions integrated in the full scale SW is still to be developed.

Finally the other phases of the mission (rendezvous and capture) are still in design and development. Once these goals will be achieved a complete mission will be simulated.

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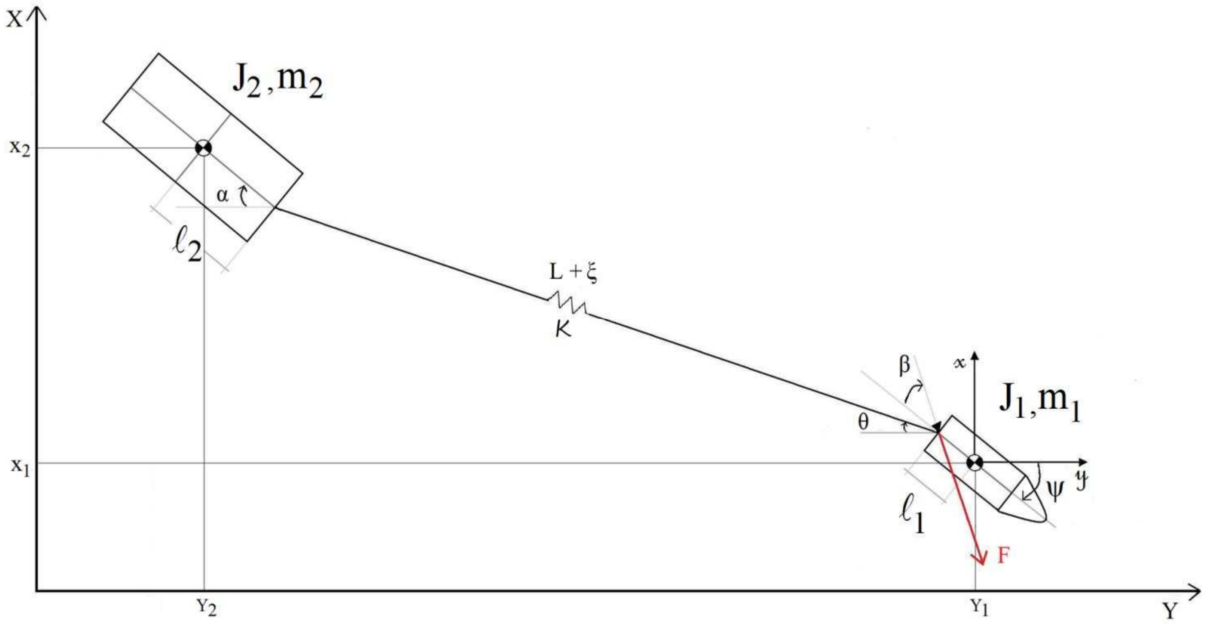

Figure 1. Geometry of tethered system in orbital plan

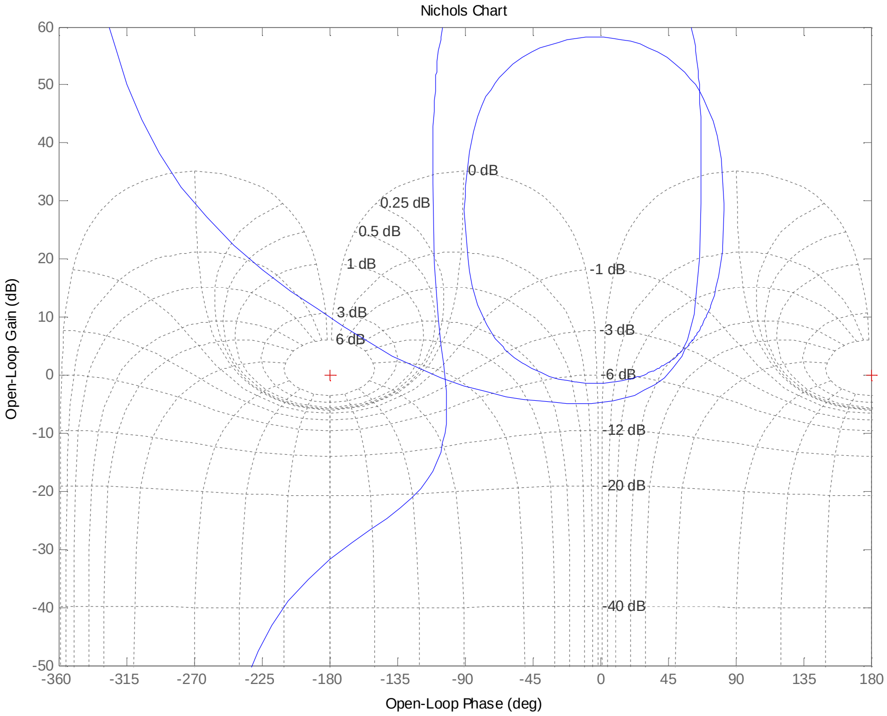

Figure 2. Nichols plot

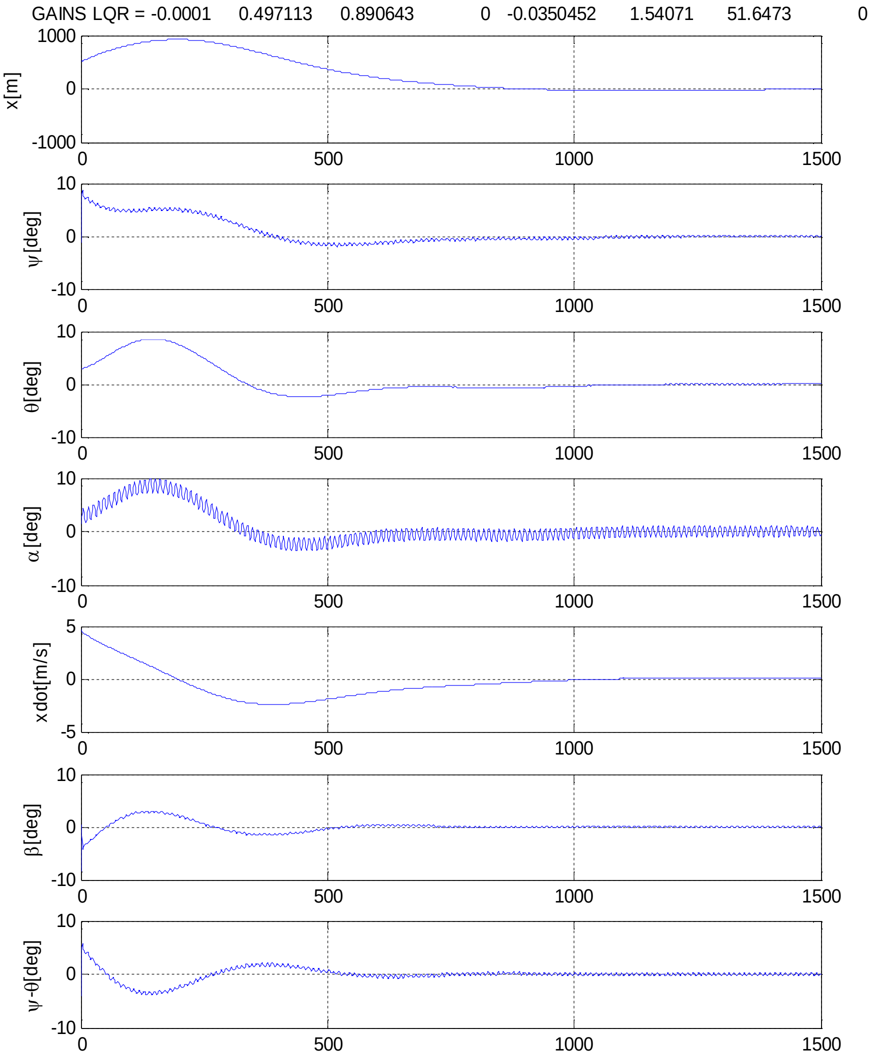

Figure 3. Time domain response in orbital plan