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INFLUENCE OF THE ATV PROPELLANT SLOSHING ON THE GNC PERFORMANCE

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ABSTRACT

The Automated Transfer Vehicle (ATV) is an ESA funded unmanned space transport vehicle designed for logistic servicing of the International Space Station (ISS). Its mission objectives are to raise the ISS orbit (ISS re-boost), to deliver pressurized and unpressurized cargoes to the station, to refuel the ISS and to provide a waste disposal capability.

The ATV Flight Segment (FS) is equipped with 8 propellant tanks, which may contain up to 7 metric tons of liquid propellant. When compared to the 10 to 13 metric tons ATV dry mass, it is clear that the propellant mass may induce a significant perturbation on the ATV control (in terms of accuracy and propellant over-consumption).

The propellant tanks design is based upon the surface tension concept, which means that the liquid is free to move within the tanks and that its interaction with the tanks must be taken into account in the description of the ATV dynamics.

The first part of the paper describes the logic that was chosen to analyze the interaction between the sloshing phenomenon and the GNC algorithms.

The second part of the paper shortly describes the ATV-to-ISS docking maneuver, which is the most critical ATV maneuver with respect to the GNC performance and to the sloshing phenomenon. In this part is defined the maximum perturbation due to the propellant sloshing that can be accepted by the ATV GNC during this docking maneuver.

In the third part of the paper, Computational Fluid Dynamics (CFD) simulations of the docking maneuver are presented, and their results are compared with the GNC requirements.

The last part of the paper deals with the design and validation of mechanical models of the sloshing phenomenon, based on springs and pendulums, which are included in the GNC simulation tools.

1. ATV OVERALL PRESENTATION

1.1 Mission objectives

The Design Reference Mission of the Automated Transfer Vehicle is to contribute to the logistic servicing of the International Space Station. Its mission consists of:

- propulsive support to ISS orbit and attitude control,
- ISS refuel,
- delivery of cargo in pressurized environment, water and gas,
- disposal of waste cargoes.

The delivered cargo consists of:

- refuelling propellant: up to 860 kg, comprising 306 kg of fuel (UDMH) and 554 kg of oxidizer (NTO);
- dry cargo in pressurized environment: up to 5 500 kg of crew supplies, scientific experiments, logistics;
- water: up to 840 kg;

- gases: up to 100 kg of air, N2 and O2 (2 types of gas per flight only with a ratio of 50 to 50% or 33 to 67%).

The disposed cargo, safely destructed together with ATV during its re-entry, consists of:

- up to 5500 kg of wastes in pressurized environment,
- up to 840 kg of liquid wastes.

The ATV cargo transportation capability amounts to at least 7000 kg of net cargo (7500 kg is targeted), that is the cargo actually transferred from ATV to ISS or used by ISS for reboost and attitude control. This overall cargo set includes a combination of cargo items and reboost propellant that is specific to each mission. Thanks to its design, ATV has the capability to accommodate different combinations of cargo items within the ranges mentioned above. Each combination of cargo items is defined by ISS on the basis of its logistics servicing requirements and it is specified in the flight and cargo manifests.

The ATV is designed to be launched by ARIANE 5. It shall perform missions all over a ten year period, with an average mission rate of 0.7 time a year (first launch scheduled in 2004).

A general overview of the development of the ATV can be found in [R1].

1.2 ATV mission description

The ATV system shall be operational from late 2004, servicing the ISS about 8 times until 2012. ATV missions will be run with an average 15 months interval between each mission. Every mission of the ATV is built on the basis of a required combination of cargo items, refueling and reboost capabilities staying within ATV overall performances.

The ATV performs a few day flight from ARIANE 5 injection until docking at ISS on the Russian Service Module, on its aft docking port. The reference mission includes separation from ARIANE 5, transfer to a phasing orbit, phasing with the ISS and rendezvous manoeuvres leading to the docking. The whole sequence can last up to three days in nominal case. After an attached phase (including ISS re-boost sequences) that can last up to six months, the end of the mission consists in departure from ISS, de-orbitation and atmospheric re-entry.

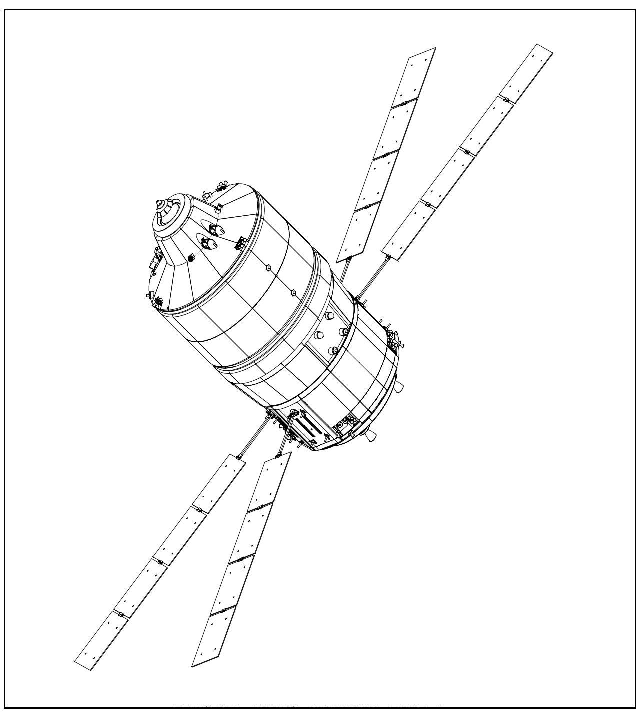

Figure 1 : ATV free flight configuration

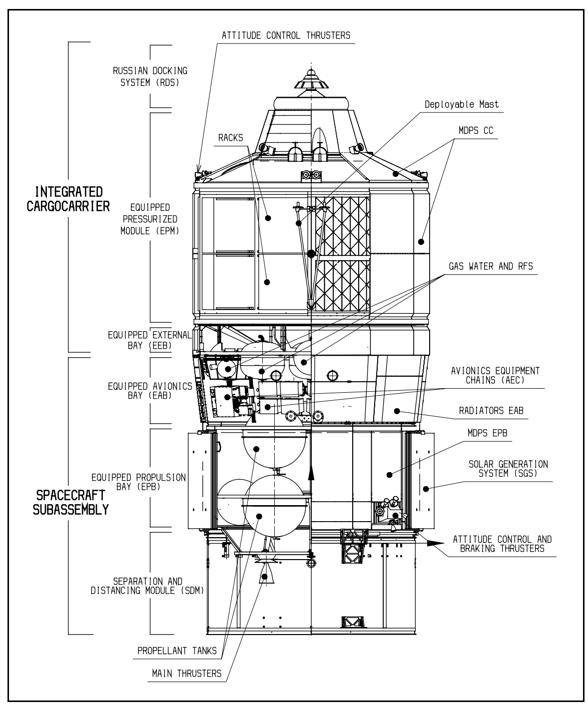

Figure 2 - General view of the ATV

1.3 Historical background

The ATV project was initiated in the late 80's through ESA funded preliminary concept analyses for an autonomous unmanned transportation system. A predevelopment study phase mainly led by DASA (now Astrium GmbH) started in the mid 90's and involved several European space companies, including Aerospatiale (now EADS Launch Vehicles).

The development phase started in the late 90's with Aerospatiale as prime contractor. This phase involves the following European space companies: Contraves Space, Alenia Spazio, Fokker, DASA and MMS (now Astrium SAS, in charge of the avionics chains).

This program represents a major challenge for the European space industry since the ATV is designed to be the first European space vehicle to perform an orbital rendezvous.

2. INTRODUCTION TO THE PROPELLANT SLOSHING ANALYSIS

The ATV spacecraft is equipped with 8 propellant tanks, filled with Mono-Methyl Hydrazine (MMH) and Mixed Oxides of Nitrogen (MON). The propellants are loaded in 2 sets of 4 identical spherical tanks (diameter = 1.1 m). Four tanks (2 MON and 2 MMH) are laid out in the upper set, and the 4 other tanks (2 MON and 2 MMH) in the lower set, as sketched in figure 3.

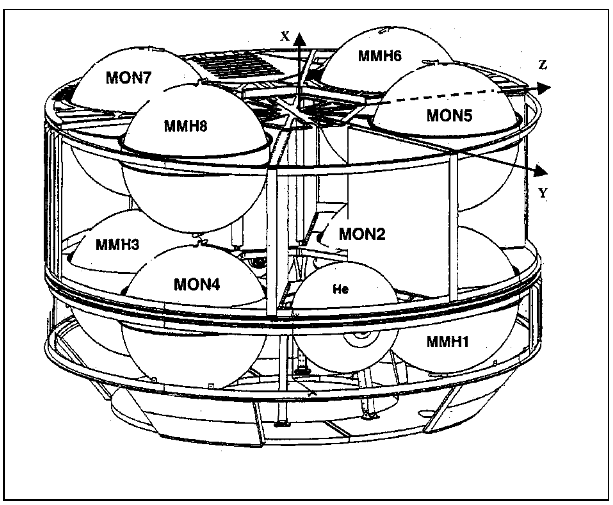

Figure 3 : ATV propellant tanks

Fully loaded tank	MON	1230 kg
	MMH	745 kg
Half filled tank	MON	615 kg
	MMH	372.5 kg

Table 1 : Propellant mass in each tank

The loaded liquid propellant mass may reach 7 tons, compared with the 10 to 13 tons ATV dry mass. As the propellant management is based on the surface tension concept, the fluid is free to move in the 8 tanks and important interaction loads may appear between the fluid and the tank walls. The loads induced by the sloshing fluids have to be known as well as possible such in a way their effect on the GNC performance is known with an acceptable reliability level. The sloshing effect has to be known and forecast in order that the GNC software may manage this perturbation and gain its effect on:

- the propellant consumption,
- the vehicle position and velocity accuracy requirements.

Specific sloshing analysis has to be led for all ATV flight phases: orbit control boosts, free drift, slew maneuvers, homing boosts, closing boosts, final rendezvous to ISS maneuver.

In this paper, the stress is laid on the final rendezvous phase (or "Docking phase"), which is the most challenging one and the most critical one with respect to the GNC performance. Extensive analyses of the sloshing phenomenon have therefore been performed for this specific case and are presented hereafter.

3. SLOSHING ANALYSIS PROCESS

The overall study logic is described in figure 4. It can be summarized in six successive steps:

1) Define requirements for the sloshing perturbations (maximum forces and torques) derived from the GNC requirements; the first analysis clearly showed that these requirements could not be met without an anti-sloshing device;
2) Design an anti-sloshing device from preliminary CFD (Computational Fluid Dynamics) computations, based on elementary simulations;
3) Compute sloshing forces with CFD simulation tool using GNC acceleration profiles that are typical of a docking maneuver; by comparing the computed sloshing forces and torques to the GNC requirements, the efficiency and the relevance of the design of the anti-sloshing device is checked;

if necessary, a new device may be designed (back to step 2);

4) Build sloshing mechanical models that are consistent with CFD results, and include them into GNC simulators to assess the GNC performances in a closed-loop process with the sloshing perturbation.
5) Run GNC simulations in closed-loop with the sloshing mechanical models, checking that the GNC requirements are fulfilled;
6) Run CFD simulations using the GNC acceleration profiles updated in step 5; compare the computed CFD sloshing forces and torques to the ones forecast by the mechanical models in closed-loop with the GNC algorithms; if both CFD and model sloshing perturbation forces are consistent, the closed-loop GNC/sloshing is then validated, and therefore the overall analysis process is. If not, it means that the sloshing mechanical models are not accurate enough and must be upgraded (back to step 4).

Such a logic allows us to avoid a much heavy and risky logic, that would require the full coupling of the GNC algorithms with the sloshing computations performed by CFD tools. Indeed the usual CFD tools require very large computation duration, that is incompatible with GNC analysis requirements (large number of simulations, Monte-Carlo analyses). Moreover the coupling of a CFD tool with the GNC algorithms, if possible, is a very challenging task, that may lead to difficult to analyze results (e.g. influence of the numerical noise in the CFD results).

4. GNC REQUIREMENTS DURING THE DOCKING MANEUVER

The ATV-to-ISS docking maneuver includes the last 25 meters before physical contact with the ISS. During this phase, ATV approaches the ISS with a closing velocity ranging from 5 to 10 cm/s, and performs a 6 degree-of-freedom control to fulfill the following requirements in terms of relative position and velocity with respect to the ISS docking port at the moment of the first contact with ISS :

Position accuracy Y, Z	*< 10 cm*
Attitude accuracy	*< 5°*
Velocity accuracy X	*< 5 cm/s*
Velocity accuracy Y, Z	*< 2 cm/s*
Angular rate accuracy roll	*< 0.4 °/s*
Angular rate accuracy pitch/yaw	*< 0.15 °/s*

Table 2 : GNC requirements at the docking to ISS

From these requirements of the overall GNC are deduced requirements for the flight control only and then for the sloshing perturbation only. From the GNC accuracy budget, the sloshing perturbation shall represent no more than 10% for the attitude budget and 5% for the lateral position and velocity budget (because of their more critical control) :

Position accuracy X	*< 0.5 cm*
Position accuracy Y, Z	*< 0.5 cm*
Attitude accuracy	*< 0.5°*
Velocity accuracy X	*< 0.1 cm/s*
Velocity accuracy Y, Z	*< 0.1 cm/s*
Angular rate accuracy roll	*< 0.02 °/s*
Angular rate accuracy pitch/yaw	*< 0.02 °/s*

Table 3 : GNC requirements allotted to the sloshing perturbation

The next step is to determine maximum sloshing forces and torques (F_{slosh}, M_{slosh}) that can be managed by the GNC. GNC simulations are therefore led for the docking phase and include a parametric sloshing model. In this preliminary stage, the sloshing model is an open-loop sinusoid function whose frequency is chosen wrt the typical acceleration of the phase.

From [R2], the first sloshing mode period can be written as:

$$T_{slosh} = \frac{2\pi\sqrt{R}}{\lambda(h/R)\sqrt{\gamma}}$$

- λ = empiric tuning parameter
- R = tank ray
- h/R = tank filling ratio
- γ = acceleration of the tank

From the typical acceleration profiles provided by ATV thrusters during the docking phase, it is possible to determine typical values of the sloshing period :

γ_{ATV}	T_{slosh}(h/R = 0.5)	T_{slosh}(h/R = 1)	T_{slosh}(h/R = 1.5)
[1 mm/s² ; 6 mm/s²]	[39 s; 103 s]	[35 s; 87 s]	[28 s; 68 s]

Table 4 : Typical periods of the sloshing phenomenon

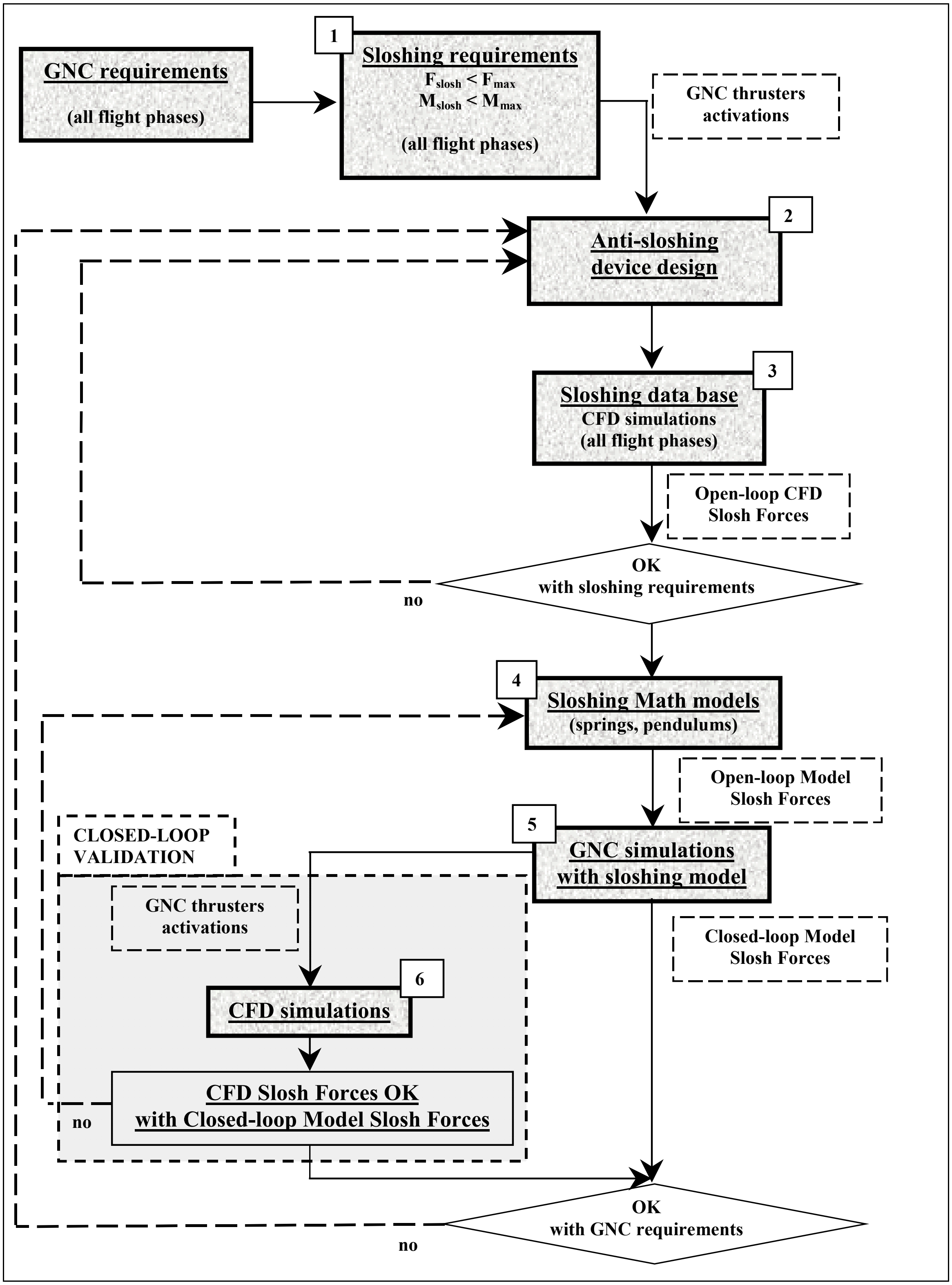

Figure 4 : Propellant sloshing analysis process

The GNC Monte-Carlo analyses lead to the following requirements for the low frequency sloshing perturbation :

SLOSHING PERIOD	SLOSHING REQUIREMENT	
	FORCE	TORQUE
20 s	4 N	9 Nm
50 s	3.5 N	25 Nm
125 s	4.2 N	50 Nm

Table 5 : Maximal sloshing perturbation allowed by the GNC requirements

It is important to note that these requirements were gained by modeling the sloshing perturbation by a sinusoidal function, without any attenuation. This non-attenuation hypothesis is very pessimistic, as the anti-sloshing device will certainly induce a very large attenuation to the propellant motion and thus to the sloshing perturbation forces and torques.

However, it can be concluded that the maximum sloshing forces and torques allowed by the GNC are very low, and that the sloshing effect can not be neglected in the GNC analyses.

5. SLOSHING CHARACTERIZATION

The purpose of this section is to provide an as good as possible description of the sloshing phenomena that may occur into the propellant tanks during all the ATV flight phases. The maximum sloshing forces and torques and natural frequencies that are gained have to be compared to the sloshing GNC requirements.

This characterization is very challenging as the actual sloshing forces are close to the precision of the available CFD tools. Besides, the low (and often zero-valued) ATV accelerations induce a hydrodynamics regime that may be partly gravity dominated, inertial dominated or even capillary dominated. The CFD that was chosen to model ATV propellant sloshing is FLOW-3D®, which a particularly accurate tool in case gravity dominated regimes. Analysis of the fluid Bond number during the docking has been performed and showed that a gravity dominated regime is present during the whole docking phase, allowing the use of the FLOW3D® software.

With the up-to-date propellant tanks draining management, only 4 tanks may be partly filled at the same time (firstly the upper ones as the lower ones are fully loaded, then the lower ones when the upper ones are empty). Consequently the FLOW-3D model that was developed included only the 4 tanks of one set. The lower set was chosen as it is further from the ATV center of mass and will lead to higher sloshing torques.

Preliminary CFD analyses clearly showed that it was impossible that the sloshing forces and torques fulfill the GNC requirements without the help of a specific device laid out in each tank. Such a device was designed to reduce as much as possible the fluid motion in the tanks with an as little as possible increase of mass. The chosen anti-sloshing device is presented in figure 5.

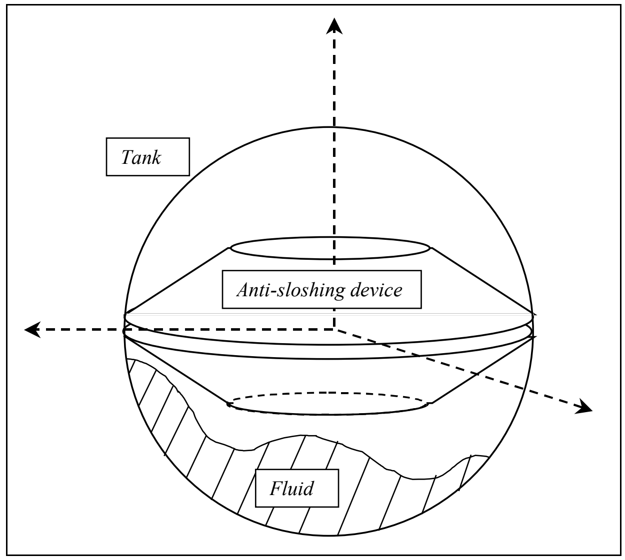

Figure 5 : Anti-sloshing device design

Thanks to this anti-sloshing device, a significant reduction of the sloshing forces and torques is gained on elementary simulations (constant input acceleration).

Analysis of the docking phase

As the ATV motion during the docking phase is 6 d.o.f. controlled, typical acceleration profiles are made of pulses in all 6 d.o.f.. These pulses induce a linear mean acceleration that remains quite low (about 10^{-3} m/s²) and inconstant. Such acceleration profiles induce a slow motion of the liquid inside the tank, the fluid moving from one tank wall to another, without having a real pendulum-typed sloshing behavior.

The influence of the filling ratio was also checked, showing that maximum sloshing forces and torques were found for filling ratios ranging from 30% to 70%.

The maximum sloshing forces and torques (with a period from 10 s to 50 s) that are gained in the CFD simulations are in the same order of magnitude as the GNC requirement. It can therefore be concluded that the sloshing phenomenon can not be neglected and will have a significant influence on the GNC performance at docking.

In order to analyze precisely the influence of the sloshing phenomenon on the GNC performance, it is therefore necessary to build mechanical models that shall be included in the GNC simulation tools to perform GNC/sloshing closed-loop simulations.

6. SLOSHING MECHANICAL MODELS DESCRIPTION

As it is shown in § 5, the sloshing perturbation can not be neglected during the docking phase. Therefore the ATV GNC simulators require a model for the propellant masses that may slosh.

The major requirement for the model is to compute forces and torques due to the interaction between the ATV and the propellant masses loaded in the propellant tanks. The models shall take into account the influence of the anti-sloshing device that the 8 propellant tanks are equipped with. Another requirement for the modeling is to build a model that is as simple as possible, in order to reduce the number of tuning parameters and to keep all results easily understandable.

A major parameter of the model is the amount of liquid mass M_1 that will be sloshing in the tank. This mass is computed as follows:

$$M_1 = [1 - \lambda(\tau_R(i))] M_L(i)$$

with:

- $M_L(i)$: ergol mass in the tank i,
- $\lambda(\tau_R(i))$: tuning parameter, depending on the filling ratio τ_R of the tank i,
- $\tau_R(i) = M_L(i) / Max(M_L(i))$: tank i filling ratio.

The function that links the λ parameter to the tank filling ratio must fulfill the 2 following constraints:

- if $\tau_R = 1$, then $\lambda = 1$: this means that when the tank is fully loaded, the sloshing mass tends to 0, and the computed sloshing force will equal the force that would create a rigid body,
- if $\tau_R \to 0$, then $\lambda \to 0$: this means that when the tank gets empty, the whole fluid is sloshing, and the computed sloshing force is mainly due to the mechanism.

Between these two limits, values of λ were chosen from the FLOW3D computations that were led considering various filling ratios. The evolution of λ with respect to the filling ratio is given in the sketch hereafter:

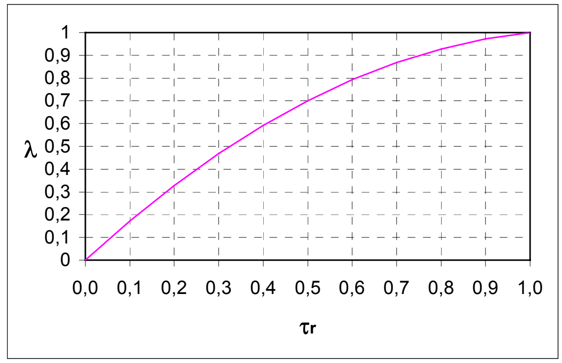

Figure 6 : Evolution of λ wrt τ_R

The major difficulty of the modelling remains in the choice of the mechanism that is to be used to compute the sloshing force. In order to keep the modelling simple and easy to analyze, only spring and pendulum mechanisms were considered. The analysis of the fluid motion during the docking maneuver showed that most of the fluid did not have any motion at all, and that only a fraction of the fluid was slightly moving from one tank wall to another, behaving like a spring mechanism. In such a case, the most relevant modelling is not the classical pendulum model, but a spring mechanism applied to a point mass.

The sketch hereafter represents the mechanical model that is used to compute the forces and torques due to the propellant inside one tank :

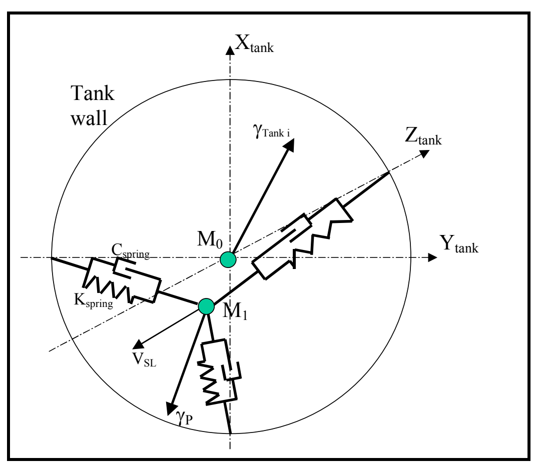

Figure 7 : Sloshing mechanical model for the docking phase

with:

- M_1: liquid mass with a pendulum typed motion,
- M_0: liquid mass motionless in the center of the tank,
- $\vec{\gamma}_P$: non gravitational acceleration applied on the point mass:
  - $\vec{\gamma}_P = -\left(\vec{\gamma}_{Tanki} + \frac{d\vec{\Omega}}{dt} \otimes \vec{P}_{SL}(i) + \vec{\Omega} \otimes \left(\vec{\Omega} \otimes \vec{P}_{SL}(i)\right) + 2\vec{\Omega} \otimes \vec{V}_{SL}(i)\right)$
  - $\vec{\gamma}_{Tanki}$: acceleration of the tank i,
  - $\vec{\Omega}$: ATV angular rate,
  - $\vec{P}_{SL}(i)$: position of the liquid mass inside the tank i in the tank frame,
  - $\vec{V}_{SL}(i)$: velocity of the liquid mass inside the tank i in the tank frame,
- K_{spring}: stiffness of the spring mechanism,
- C_{spring}: damping of the spring mechanism.

Stiffness and damping coefficients (K_{spring}, C_{spring}) remain identical whatever the direction. This model can be used identically for each of the 8 propellant tanks, by considering specific input data for each tank (loaded propellant mass, local acceleration). The computation of the stiffness is linked to the natural frequency of the liquid motion inside the tank. This frequency depends mainly on:

- the local acceleration,
- the filling ratio.

The damping coefficient computation is made in a similar way as the stiffness one. The process is nevertheless simplified because the damping coefficient is supposed not to depend on the filling ratio, but only on the liquid mass.

7. GNC/SLOSHING CLOSED LOOP VALIDATION

All the sloshing simulations performed to tune the mechanical model were performed through an open-loop process, by using GNC acceleration input that had been computed without any sloshing model. The purpose of this chapter is to complete the models validation by performing GNC/sloshing closed-loop simulations. This task corresponds to the step 6 of the overall study logic (see figure 4).

7.1 Closed-loop analysis logic

A good way to perform GNC/sloshing closed-loop simulations would be to include CFD computations inside the GNC simulation tool. As this process is very complex to perform, a quicker method was chosen. In order to assess the coupling between the GNC and the sloshing effect, the mechanical models that are described in §6 are included in the GNC simulation tool. GNC/sloshing closed-loop simulations can then be performed, and the acceleration profiles are afterwards used as input to new CFD runs:

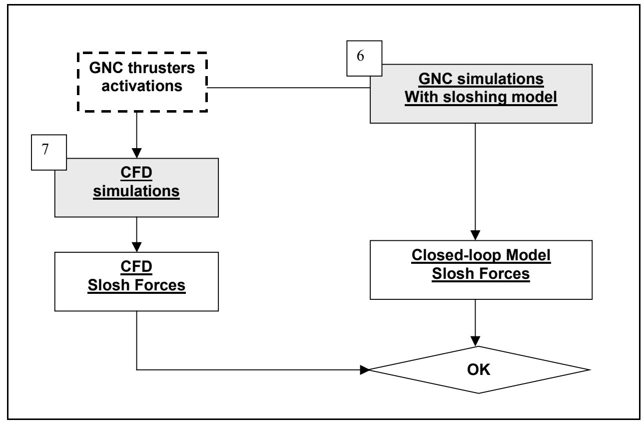

Figure 8 : Closed-loop validation logic

7.2 Closed-loop analysis results

The FLOW3D computed perturbation forces are presented on figure 9. It can be noted that the maximum force level (3.5 N) does not exceed the GNC requirement for the docking phase.

The comparison of the FLOW3D perturbation forces and the model ones is also given in figure 9. There is a very good agreement on this comparison. The force levels are correctly reproduced by the model, and the natural frequencies are also very similar.

This very good agreement leads to the conclusion that the GNC simulations would be similar if FLOW3D was included inside the GNC simulation tool. The GNC/sloshing closed-loop process is therefore correctly validated during the docking phase.

FIGURE 5.4

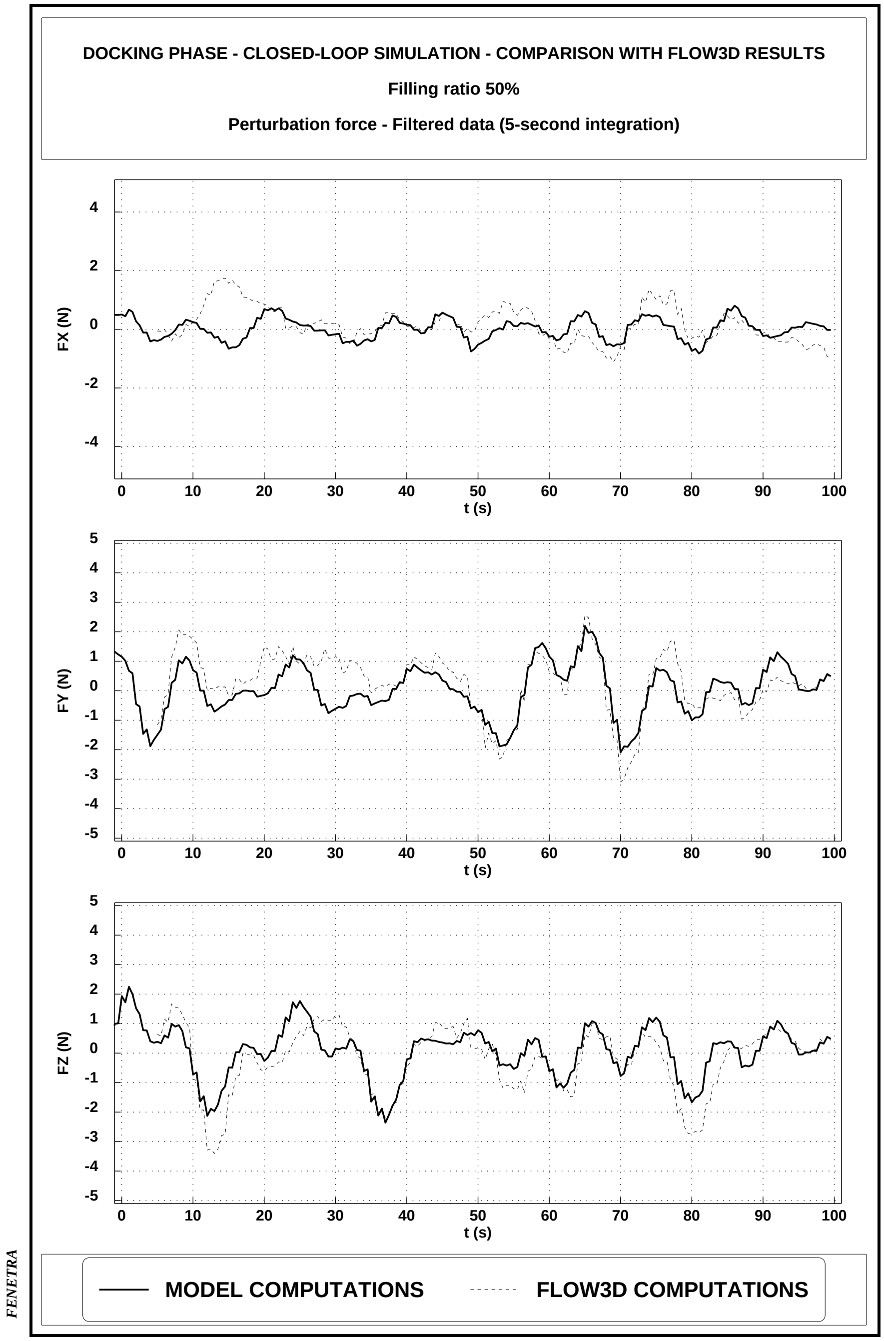

Figure 9 : FLOW3D / mechanical model compared results

CONCLUSION

This paper describes the ATV propellant sloshing phenomenon and its influence on the GNC performance during the final rendezvous to ISS phase. The complete analysis logic is presented, including a description of the sloshing phenomenon through CFD simulations, the definition of equivalent mechanical models of the sloshing and their integration in the simulation tools. The results of the GNC/sloshing closed-loop simulations are finally compared with CFD computations, and clearly show that the sloshing forces are correctly reproduced by the equivalent model, allowing an accurate definition of the ATV dynamics and a good estimation of the GNC performance.

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