The AOCS' effects on the Propulsion Subsystem using the ESPSS Satellite Library

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Abstract

The paper describes the phase 3 of the work performed for the implementation and validation of a satellite platform propulsion system modelling library ESPSS (European Space Propulsion System Simulation) within the existing tool EcosimPro®.
EcosimPro® is a Physical Simulation Modelling tool that is an object-oriented visual simulation tool capable of solving various kinds of dynamic systems represented by writing equations and discrete events. It can be used to study both transients and steady states. The object oriented tool, with the propulsion library ESPSS for example, allows the user to draw (and to design at the same time) the propulsion system with components of that specific library with tanks, lines, orifices, thrusters, tees. The user enhances the design with components from the thermal library (heaters, thermal conductance, radiators), from the control library (analogue/digital devices), from the electrical library, etc.
The paper will present several new components added to the propulsion library as well as some example. Those improvements have been performed in the phase 3 of the development of ESPSS consisting of updating and extending multiple libraries to represent a functional propulsion system, e.g. fluid properties, pipe networking including multi-phase fluid flow, two-phase two fluids tanks with gravity or accelerations effects, non-adiabatic combustion chambers, chemistry, turbo-machinery, etc.
The paper presents the modelling of propulsion system performed in order to check the implementation of the new components especially the components dealing with the effects of the mission on the propulsion sub-system. In particular, the accelerations generated by thrusters, reaction wheels and other satellite components have an influence on the fluid-dynamic behavior of the propulsion system. Moreover, the propellant tanks fill level influences the satellite's center of gravity and moments of inertia, which can in turn have an effect on the pressure and flow conditions in fluid lines. The use of the ESPSS satellite library for being able to model some interactions between the AOCS and the propulsion system will be presented. A full satellite missions, for example an orbit transfer from GTO to GEO will be presented and particular behaviors highlighted.

1. Introduction

The paper presents first a simulation concept that is a system engineering tool dedicated for complex systems, the European Space Propulsion System Simulation (ESPSS) libraries, and in a second part a specific SATELLITE library dedicated first for assessing the evolutionary behaviour of components and the AOCS's effects on the propulsion sub-system.

2. ESPSS background

EcosimPro® is a Physical Simulation Modelling tool developed for ESA by Empresarios Agrupados Internacional (Spain) since 1989. EcosimPro® was a precursor and now with its 24 years of careful growing it belongs to the last generation of the common engineering tools after computer aided design (CAD) and integrated engineering analysis tools available on classical laptops. The kernel of EcosimPro® is an expert solver of all the equations set in the different components of a system. Thanks to such expert solver, the tool allows to manipulate components like objects that can be independently further developed with more sophisticated equations. EcosimPro® is based on a visual simulation tool for solving simple and complex physical processes that can be expressed in terms of equations (including ordinary differential and differential-algebraic) and discrete events.
Practically, the modelling of physical components is based on a basic “EcosimPro language” (EL), an object-oriented programming language which is very similar to other conventional programming languages (Basic) but is very powerful to write any equations and differential equations for modelling continuous and discrete processes. EcosimPro employs a set of libraries containing various types of components (mechanical, electrical, pneumatic, hydraulic, etc…) which can be interconnected to model complex multi-domain dynamic systems. The ESA European Space Propulsion System Simulation (ESPSS) is a set of EcosimPro® libraries written to model all aspects of a functional propulsion system. As a tool ESPSS is relying on 1D flow equations, thermodynamic relationships and real fluid properties, there is no need for fudge factors, therefore the results of the simulation could be considered as general as long as the flow is one-dimensional and homogeneous (either as mono-phase, or two-phase state or as a mixture).

The Libraries section describes those libraries, focusing on their physical modelling. Some realistic cases of interest are chosen to give an overview of the capabilities of the software.

3. ESPSS Libraries

The following libraries have been developed in the phases 1&2 of the project ESPSS: “Fluid Properties”, “1-D Fluid Flow”, “Tanks”, “Combustion Chambers” and “Turbomachinery” libraries. An overview of these propulsion libraries with some validation cases is presented in [R 1].
As the third phase of the project ESPSS started July 2011, only the new improvements are discussed in the following chapters. One among them is the new Steady-State library compatible with other parts of ESPSS along with two new libraries for satellites: the Electric propulsion library (EP library) and the SATELLITE library. Those improvements will be added for the next release of ESPSS to its users [R 2].

4. ESPSS Improvements

The improvement of ESPSS are numerous, here are reported only some significant points:
In the Junction components the supersonic conditions are allowed as option, and can be detected automatically.
The heat Exchanger have been upgraded for cross flow dispositions accounting for several baffles and tube passes.
A more robust version of the Cold Thruster component using supersonic junctions (non adapted conditions can be calculated included the shock inside the nozzle).
Valves have been upgraded to consider EqualPercentage, Linear, QuickOpening or user-defined laws.
Fluid Cavities (not the simple Volumes) and Tank models account for the volume expansion due to wall compressibility.
Added new input data and options for right, "Y" and User defined Tee component.
Nozzle & chamber diameters reconstruction is included in the continuous block allowing geometry redefinition during a simulation.
New components are available for imposed static boundary conditions (intakes).
N_2, He, O_2, H_2, CH_4 real properties files are rebuilt with more points in pressure & temperature. Moreover, extrapolating in real properties at $P>P_{max}$, $T<T_{min}$ or under two-phase flow is better detected and treated.
1D Tanks include film boiling bubbles formulation (as a new option) and better simulation of the generalized boiling process.
Condensation (raining) flow is now optional: Droplets can remain as a fog in the ullage volume or can drop to the liquid volume at a given speed.
Pumps model: Table of loss of head vs. net positive suction head (NPSH) and compressibility effects due to pump cavitations have been included.
Combustor models are more robust simulating start-ups and shutdown sequences.
New components are available to compute the delay in the transport of the combustion products also permitting the simulation of a mixture of combusted gases and pure fluids (chamber with more than 2 injectors).
In addition a new library called STEADY has been added to ESPSS for the simplified cases of Steady states. The

STEADY library contains a complete set of components (combustors, cooling-circuits, nozzles, turbines, pumps and valves) able to calculate the performances of any rocket engine cycle type under design and off-design conditions.
The STEADY_EXAMPLES library contains a set of cycles types with examples helping the user building models.
Design models contain the design conditions (normally non-dimensional engine's performance) as part of the components' input data. Experiments built with the default partition (automatic ordering of the whole cycle equations made automatically by EcosimPro) will calculate the operational values of the cycle. And the analyses (off-design) of the models contain the operational conditions as input data. Off design conditions will be calculated accordingly with the varying boundary conditions and using the performance maps of turbines and pumps.
The STEADY library has been prepared to run design and off-design calculations using an only model by means of the design partition that is an EcosimPro capability to transform the operational data to unknowns adding the design conditions (efficiencies, chamber pressure, etc.) as boundaries.
The EP library allows the user to simulate the operations needed to activate the electric propulsion aboard a satellite and to simulate the outputs of the several telemetries and functional characteristics. In addition this library includes a port so called "RAMS" for simulating some predetermined failures cases for each components.
Finally a new library deals with interactions of the Satellite Attitude and Orbit Control System (AOCS) with its propulsion subsystem. This library, to be added to ESPSS future releases, has been named SATELLITE and is described in more detail below.

5. Satellite Library

The satellite library contains the main components needed to build a satellite AOCS with the major interactions and perturbations that occurs in flight [R 3],[R 4][R 5].

- Moon and Sun perturbations, mainly corrected by the use of thrusters for the North-South station keeping of a GEO satellite,
- Earth flatness or so called "J2" perturbations to be used for the heliosynchronous satellites,
- Sun pressure interaction with the solar arrays of the satellite.

In addition, a control of the satellite attitude can be added (using the existing components of the existing CONTROL library) for performing an Earth Pointing with a set of actions on the reaction wheels or on a set of thrusters. Finally the preliminary components of the library are shown in the Fig. 1.

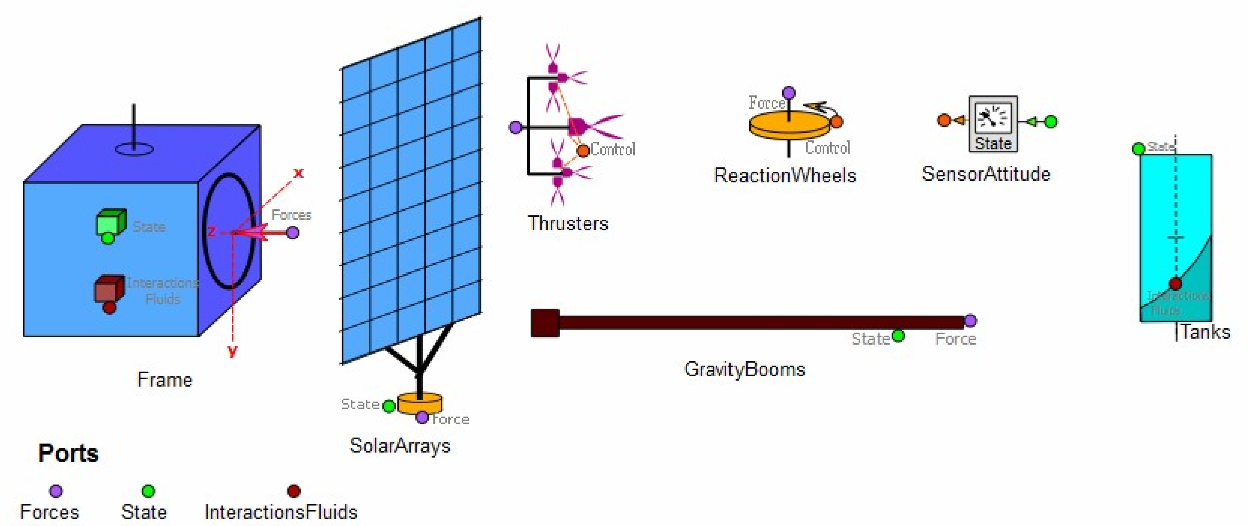

Fig. 1 Palette of components for the SATELLITE library of ESPSS.

Three ports have been added for the transfer of information between the components of the library:

- Port force: port that is multifunctional port for allowing inputs from a set of thrusters, reaction wheels (RW), solar arrays (SA) and gravity boom (GB) with the port directions set at IN for the satellite frame, OUT for all other components. The variables of the port are of type SUM in order to automatically account for all mass flow rates, forces, moment, Angular momentum and power coming from all connected components.
- Port State: port that is multipurpose port for allowing the attitude and orbit control and for 3D visualization, as well as the needed inputs for the SA, GB, Tanks and for control with the port directions set at OUT for the satellite frame, IN for all other components.

- Port InteractionsFluids: this port allow to transfer the location of the free surface of each liquid in the tanks component and the Archimedes pressure function, as well as the inertia matrix and the location of the centre of mass (COM) each liquid.

5.1. Frame component

The major component of the Satellite library is the frame component that is in charge to solve the flight dynamic with input data of the initial orbit and with non gravity forces vectors coming from the thrusters and the SA. The perturbation forces coming from Moon and Sun gravity are directly solved inside the component.
The first main equation of the component is based on the momentum equation (1) as follow:

$$\frac{d\vec{\pi}}{dt} = \vec{\Pi} \tag{1}$$

with $\vec{\pi} = \begin{pmatrix} \vec{r} \\ \vec{v} \\ m \end{pmatrix}$ and $\vec{\Pi} = \begin{pmatrix} \vec{v} \\ -GM_{focus}\,\vec{r}/r^3 + \sum\left(\vec{T}_{thrust} + \vec{P}_{perturb}\right)/m \\ \sum - thrusters\_mass\_flow \end{pmatrix}$

where ***v*** is the velocity vector of the satellite frame with respect to the Earth centred inertial frame (ECI), *GM* the gravitational constant time the mass of the focus body (Earth), ***r*** the radius vector from the focus body centre, ***T*** the resultant thrust vector, applied on the satellite COM, in ECI, ***P*** the perturbation and interaction force vector in ECI and *m* the instantaneous mass of the satellite that is corrected by the thrusters consumption if any.
The second main equation of the component is based on the dynamic equation (2) for the attitude of satellite around its COM as follow:

$$\frac{d\vec{H}}{dt} + \vec{\Omega}\wedge\vec{H} = \vec{M}_{Control} + \vec{M}_{Perturbation} \tag{2}$$

with $\vec{M}_{Control} = \left\{ M_{thruster} - \sum_i \frac{d\vec{H}_{RWi}}{dt} \right\}$ and $\vec{M}_{Perturbation} = \left\{ M_{perturb} - \sum_i \vec{\Omega}\wedge\vec{H}_{RWi} - \sum_i \vec{\Omega}\wedge\vec{H}_i - \sum_i \frac{d\vec{H}_i}{dt} \right\}$

The source terms come from the torques due to the thrusters and RW, and from the perturbation torques due to the other mobile or flexible parts of the satellite (SA, GB) and with $\vec{\Omega}$ the instantaneous rotation with respect to the inertial orientation frame of the satellite and the angular momentum with respect to the satellite of the reaction wheels $\vec{H}_{RWi}$ and of the other mobile parts $\vec{H}_i$, but with all their coordinates and derivative written in the satellite axis. The angular momentum $\vec{H}$ takes into account the possible evolutionary behaviour of the fluid in the tanks through the inertia matrix update.
The attitude angles of the satellite must be known in order to properly set the local data like the thrust with respect to the satellite frame into the ECI frame. Those can be given by the Cardan angles (yaw, pitch, roll) of the satellite axis with respect to the orbital frame. The attitude angles of the orbital frame can be given by the Euler angles (precession, nutation, proper rotation) with respect to the inertial frame ECI. But in order to ensure robustness in the solutions, the equations dealing with the attitude angles are based upon the quaternion theory. Thus the general equation of the quaternion theory (3) is to be solved simultaneously with the other previous equations.

$$\frac{dQ}{dt} = +\frac{1}{2}[Q].\Omega \tag{3}$$

This integration produces at each time *t* the quaternion $Q(t)$ that enable to retrieve (with suitable conversion matrixes) the attitude angles without any risk of singularities with unit quaternion. As the quaternion of the satellite with respect to the orbital frame is available (given by the state port) it can be used in the external control loop of the attitude of the satellite for an Earth pointing command by setting to zero its imaginary components.

5.2. Solar arrays component

For the current release of the library, a fixed SA on the satellite body or an automatic orientation of the SA with respect to the sun are considered. The component is linked to the Frame component (state port) in order to get the Satellite to Sun vector and other information.
The classic equations of sun pressure interaction on the solar array are used in this component with input coefficients of reflection, specular reflection and absorption.
The output of the solar arrays are the 3D forces due to the sun pressure, their moments and the power produced by the solar cells according to the input data of the efficiency of the solar cells.
As for other components, the solar array component is written in terms of vector to allow a number of SA (up to 4 for instance) that are all described in term of location, orientation, size.

5.3. Thrusters component

When activated, this component outputs the thrust vector with respect to the satellite, the moment induced by the thrusters forces and the mass flow rates (for mono propellant as well as for bi-propellant). In case of electric propulsion, the electric power consumption is provided as well.

5.4. Reaction wheels component

Once activated this component outputs the kinetic momentum vector with respect to the satellite as well as the electric power consumption of all reaction wheels considered.

5.5. Gravity booms component

Based on the input from the state port coming from the satellite frame component and the geometrical location of the main body, this component provides the moment vector with respect to the satellite without any forces (pure torque) for all the GB considered.

5.6. Tanks component

The classic relation for Archimedes' pressure $dp = -\rho.\gamma.(z - z_0)$ is already taken into account in the existing Flow1D tank model of the original ESPSS [R 2], but this is too restrictive. In space, the satellite is rotating around its COM (and some couples are produced by thrusters and reaction wheels, or windmill effect by the solar pressure on the SA). Further particular forces e.g. originating from thrusters or solar pressure on the solar arrays, produce acceleration. Therefore the Archimedes' pressure needs to take into account the effect of the acceleration and the effect of the rotations.
This component is quite sophisticated (including a 3D discretisation of the fluid in the tanks) because its task is to manage the location of the free surface between the liquid and gas phases for a given set of acceleration and instantaneous rotation levels, and hence allowing the evaluation of the Archimedes' pressure. Thanks to a connection from the frame to the state port, the information of acceleration and rotation are available.
The effects of combined rotation and acceleration (due to non-gravity forces) on the liquid phase location can be summarized as follow in the most general case where an instantaneous rotation $\vec{\Omega}$ and an acceleration of the satellite $\vec{A}$ are not null: one can use them for a defining a base of an instantaneous frame with Z along $\vec{\Omega}$, and with $-\vec{Y}$ along $\vec{\Omega} \wedge \vec{A}$ and $\vec{X}$ along $\vec{Y} \wedge \vec{Z}$: that means that the two given vectors $\vec{\Omega}, \vec{A}$ are in the plane XZ. The corresponding sketch and nomenclature are given in Fig. 2.

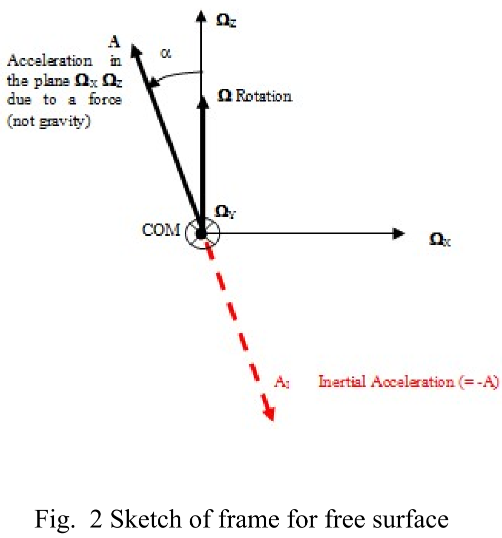

Fig. 2 Sketch of frame for free surface

This frame can be different at each time because it is defined by the acceleration that can be inertial (sun pressure forces) and the satellite can rotate, so that frame cannot be fixed with respect to the satellite body. This frame is thus an instantaneous frame.

For a point M(x,y,z) in the frame based on "Ω^A" the forces per unit of mass $\vec{f}$ is given by:

$$\begin{pmatrix} f_x \\ f_y \\ f_z \end{pmatrix} = \begin{pmatrix} \omega^2 x + A_I \sin(\alpha) \\ \omega^2 y \\ -A_I \cos(\alpha) \end{pmatrix} \quad (4)$$

where ω is the module of ***Ω***, A_I the inertial acceleration module.
The equilibrium equation of the free surface is defined by the fact that the pressure is constant and according to the liquid volume conservation. The hydrostatic general equation (i.e. a degeneration of the general Navier-Stokes) is :

$$\vec{\nabla} P = \rho \vec{f} \quad (5)$$

For a infinitesimal displacement $\vec{ds} = (dx \quad dy \quad dz)^t$ we have $\vec{\nabla} P \cdot \vec{ds} = \rho \vec{f} \cdot \vec{ds}$ which give the elementary equation $dP = \rho \vec{f} \cdot \vec{ds}$. When the small displacement belongs to the free surface, we finally get the equation of a free surface by implying $dP = 0$:

$$dP = 0 = \rho\left(f_x dx + f_y dy + f_z dz\right) = \rho\left(\omega^2 x dx + A_I \sin(\alpha) dx + \omega^2 y dy - A_I \cos(\alpha) dz\right) \quad (6)$$

The integration of the previous equation introduces a constant:

$$0 = \rho\left(\omega^2 \frac{x^2}{2} + A_I \sin(\alpha) x + \omega^2 \frac{y^2}{2} - A_I \cos(\alpha) z\right) + Const \quad (7)$$

The equation of the surface can be seen as a function of x and y with the constant Cz that shall be adjusted into each tank for fulfilling the conservation of the liquid volume.

$$z = S(x,y) + C_z \text{ and } S(x,y) = \frac{\rho}{A_I \cos(\alpha)}\left(\omega^2 \frac{x^2}{2} + A_I \sin(\alpha) x + \omega^2 \frac{y^2}{2}\right) \quad (8)\ (9)$$

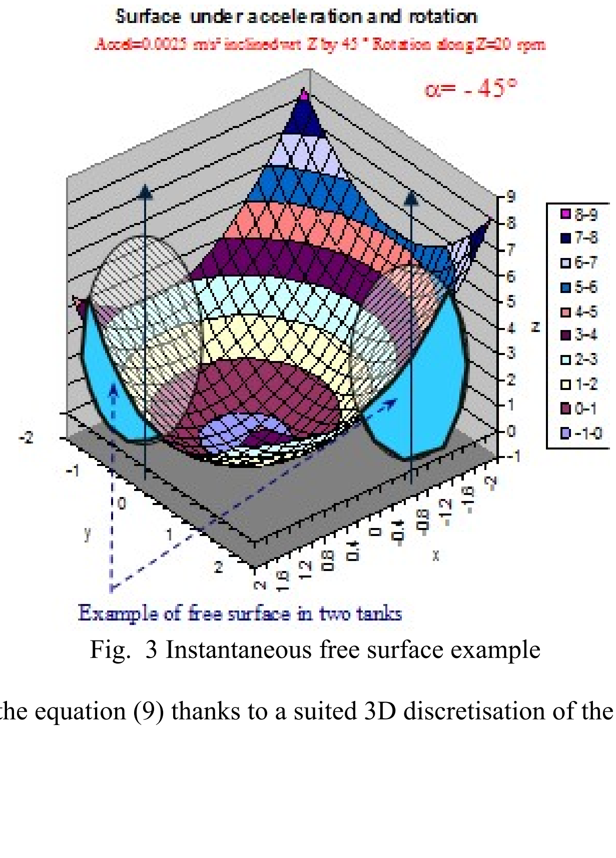

Fig. 3 Instantaneous free surface example

The Tank component solves the equation (9) thanks to a suited 3D discretisation of the tanks in small volumes.

Finally, the pressure in the liquid phase at the outlet of each tank is deduced from the free surface by the curvilinear integral along the arc from any point of the free surface to the outlet of the tank, the pressure difference is given by:

$$\Delta P_{arc} = \int_{arc} \rho \vec{f} \cdot d\vec{s} \quad (10)$$

The pressure difference in (10) can be positive or negative because the liquid can be in the opposite side of the exit of the tank while the exit is still wetted by liquid thanks to the PMD inside the tanks.
The port "InteractionsFluids" transmits all the elements needed of the dynamic function ΔP for computation into the connected main component (Satellite frame), and for each tanks considered.

6. Satellite library validation checks

The validation plan of the library includes flight dynamic validation, the attitude control validation and the tank Archimedes pressure validation as described in the next paragraphs.

6.1. Flight dynamic validation

Thanks to the equations that can take into account the perturbations of the orbit due to the Moon and the Sun, there is one obvious check that can be performed without any difficulties: it is well known that the inclination from GEO increases by the rate of up to about 1 degree per year. This has been checked with a simple model for an orbit near GEO. The results are shown in
Fig. 4.
The order or magnitude of the evolution of the orbital inclination is well respected with about 0.8 degrees after 31 millions of seconds (i;e. 1 year). This is the right rate for the date and orbit considered. The Right Ascension of the Ascending Node (RAAN or angle also called Omega) is about constant near 90° which is also the right evolution.

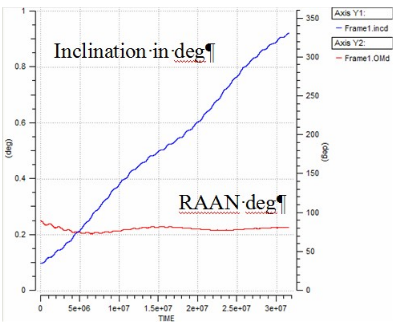

Fig. 4 GEO perturbation in 1 year

A further flight dynamic check can be performed easily when considering a heliosynchronous orbit: it is well known that by definition the Right Ascension of the Ascending Node (RAAN) shall increase by 1 degree per day. Thanks to the equations that take into account the Earth flatness (J2 term) this effect can be checked with a simple model into the SATELLITE library for an orbit near the helio-synchonism. The results are shown in
Fig. 5. The rate of evolution of the RAAN is well in accordance with the expected result. The expected value of the inclination is to stay constant as this is shown on the plot.

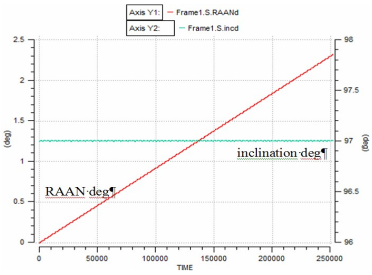

Fig. 5 Heliosynchronous perturbation in 2.8 days

Finally a third check can be performed with respect to thrust by simply applying the Edelbaum's formula for continuous thrust transfer between circular orbits: the ideal velocity (ΔV) produced for the transfer is given by the difference in initial orbit and final orbit. This ΔV can also be computed with the mass consumption for the given Isp. The check has been performed with a strategy of horizontal thrust into the orbital plane. It shows very similar values between Edelbaum's ΔV and the computed ΔV (with a difference of <0.09 %)

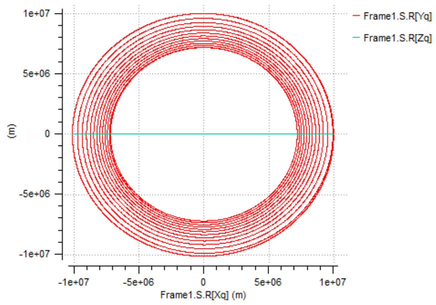

Fig. 6 Orbit transfer with continuous thrust

6.2. Attitude control validation

The attitude check has been performed with classic methods showing that after all stabilization, absolute value of angular momentum of the S/C without the reaction wheels and the one of the angular momentum of the reaction wheel are equal.

6.3. Archimedes pressure validation

The validation of the Archimedes pressure simulation was performed with the output of the free surface. A 3D tool was used to show such surface. The case of a simple acceleration along –X and Z (-1, 0, 1) is considered first. The effect of this force applied at the COM on the free surface of a tank with its axis along Z is shown in Fig. 7 in the S/C frame. The free surface is a plane inclined by 45 ° with respect to Z perpendicular to the applied force as expected.

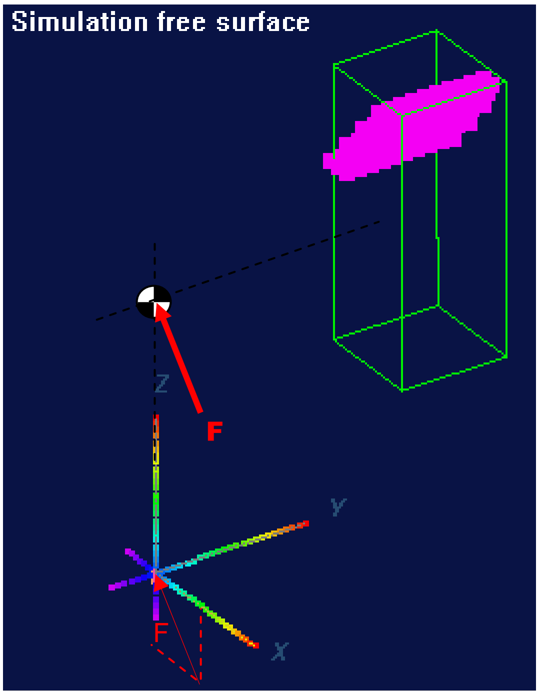

Fig. 7 Free surface simulation under force ***F***

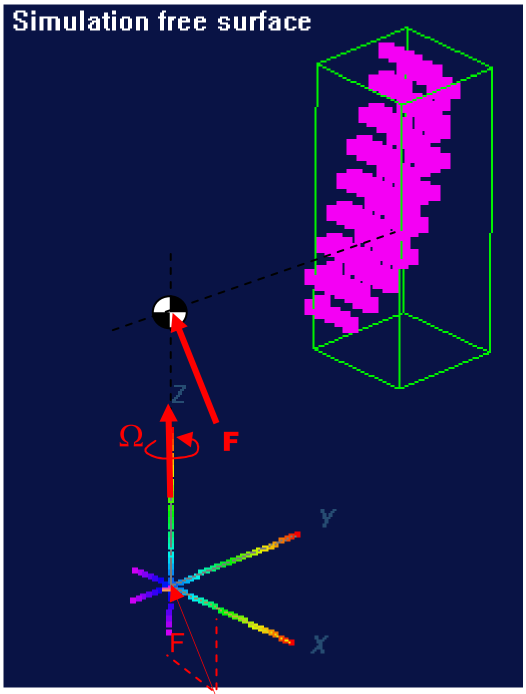

Fig. 8 Free surface under combined ***F*** and rotation ***Ω***

The more complex case of a combined acceleration along –X and Z (-1,0,1) with a rotation around Z (0,0,1) is shown in Fig. 8. The effects of such combination on the free surface of the tank are simulated within the SATELLITE library. The effect of the rotation re-orients and curves the free surface as expected in the previous sketch of

Fig. 3 , the surface becomes a part of a paraboloïd centred on the $\vec{\Omega}$ (Z axis) with a shift. The effects of the force component along X are no more visible because of the centrifugal forces around Z.

7. Modelling of Propulsion System

The modelling of propulsion system (or parts of it) is presented in order to check the implementation of the new components especially those dealing with the mission effects onto the propulsion sub-system. In particular, the accelerations generated by thrusters, reaction wheels and other satellite components have an influence over the fluid-dynamic behaviour of the propulsion system. Moreover, the propellant tanks' fill level influences the satellite's COM and moments of inertia, which can in turn have an effect on the pressure and flow conditions in fluid lines. A conceptual demonstration of these evolutionary behaviour models is described for a classical chemical propulsion system in the case of a GEO spin satellite.

The bi-propellant propulsion system comprises 4 tanks filled with MMH and NTO. The 4 tanks are disposed in cross with their outlet toward the external diameter.

The simulation model of the system has been performed within ESPSS and the SATELLITE library described before. The simplified model for the assessment of the Archimedes pressure is shown in Fig. 9. It comprises the main frame component and 3 vectorised components: the thrusters icon represent up to 13 thrusters, the reaction wheels icon represent up to 4 individual reaction wheels and the tanks icon up to 4 tanks.

For the purpose of the preliminary checks, the satellite is spinned to the rate of 60 rpm around the Y axis by using the proper activation of the thrusters and reaction wheels. The free surface of the liquids in the 4 tanks and the delta pressure Archimedes from the free surface to the outlets of the tanks are shown in Fig. 10 and Fig. 11 for the case when the tanks are almost full (200 litres). Because the disposition of the tanks is symmetric with respect to the spin axis, the two tanks filled with MMH exhibit the same delta pressure of 113 mb and the two NTO tanks exhibit the same delta pressure of 187 mb. The ratio of the two values NTO/MMH represents of course the mixture ratio.

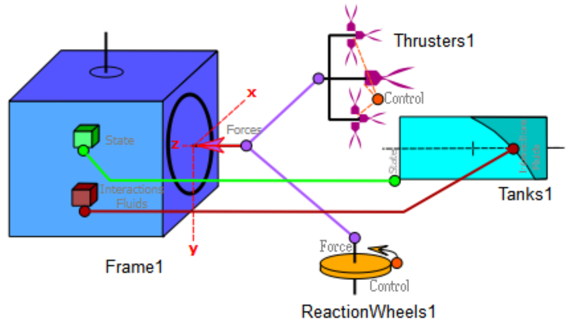

Fig. 9 Spin satellite model for evolutionary behaviour

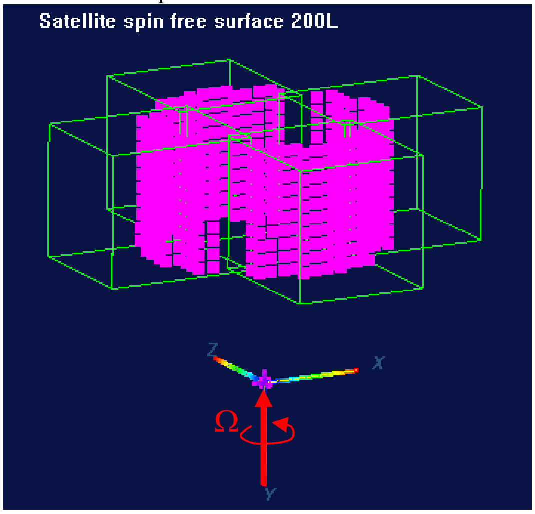

Fig. 10 Free surface of under spin, 4 tanks full 200 l.

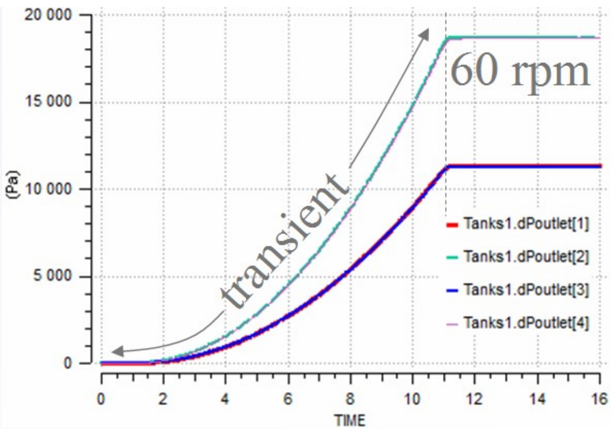

Fig. 11 Delta pressure Archimedes with 4 tanks full 200 litres under 60 rpm after 12s.

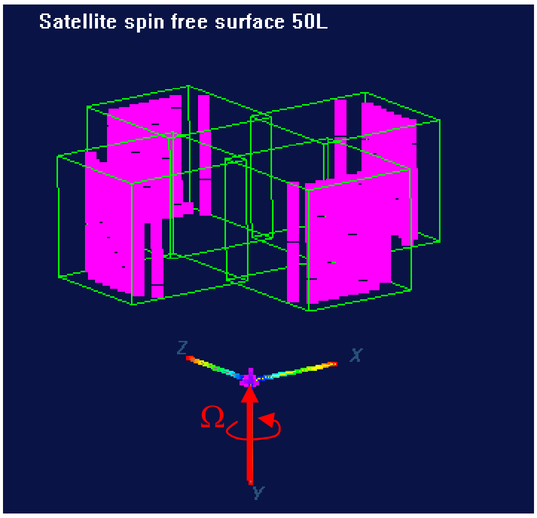

Fig. 12 Free surface of GEO spin satellite tanks 50 l.

For a different filling, the value of the Archimedes pressure is different as exemplified in when the tanks contain only 50 litres. The two tanks filled with MMH exhibit the same delta pressure of 33 mb and the two NTO tanks exhibit the same delta pressure of 54 mb. The ratio of the two values NTO/MMH represents also the mixture ratio.

8. Mission cases for a LEO and GEO satellite

In order to highlight the capabilities of the SATELLITE library, two mission's cases have been set up with the open data available.

8.1. Mission cases for a LEO satellite

The first mission case is a LEO satellite with the last "de-orbit" manoeuvre of SPOT 1 performed in Nov. 2003. The mission goal is from a quasi-circular 800 km orbit to decrease the perigee altitude down to 550 km. According to the published information, this manoeuvre was done with 4 pulses of thrust with a duration of 1000 s each.
The model used in order to simulate this manoeuvre is shown in Fig. 13. Thanks to the capabilities of the existing

libraries into ESPSS, especially the CONTROL library, the interaction between the AOCS mission and the behaviour of the fluid pressure can be simulated when a control loop is used to perform the attitude control. The control loop is mainly active to set a small spin rate for an Earth pointing orientation (around the pitch axis (Y) before the thrusters are activated and for keeping that pointing rule during the whole manoeuvre.

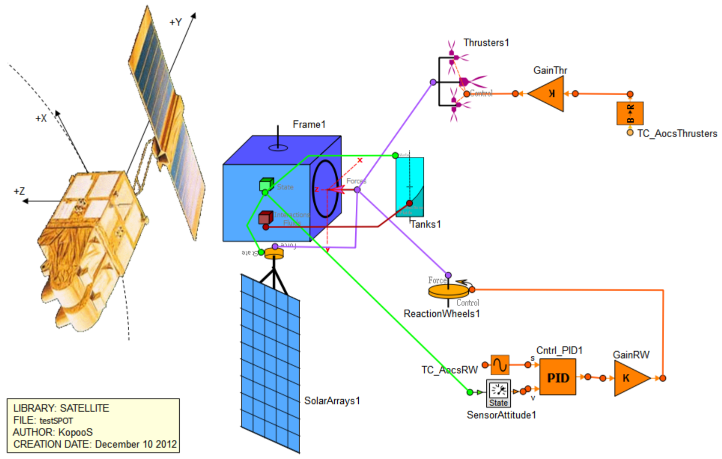

Fig. 13 LEO satellite SPOT-1 with control loop added for evolutionary behaviour

The results are shown in the following plots:
To decrease the altitude of the perigee, the thrust pulses are performed every two orbits and against the velocity, thus along –X as shown in Fig.14 with negative component of the thrust for their X components.

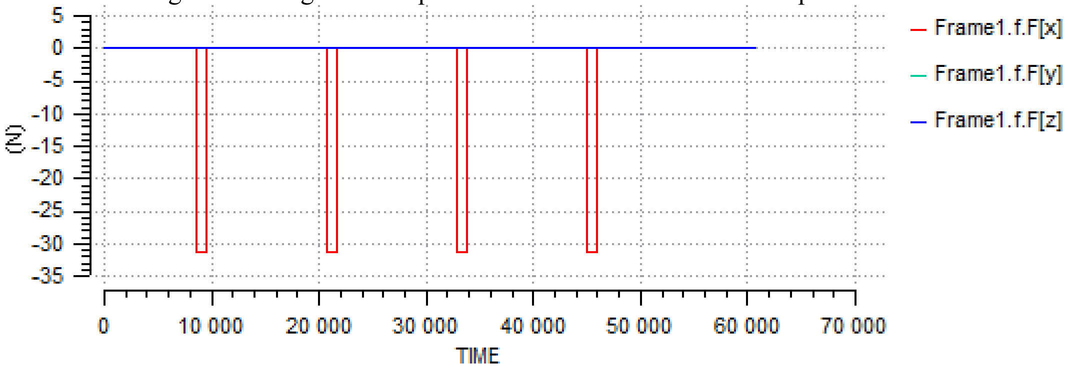

Fig. 14 Thrust sequence

The altitude followed by the satellite (Fig. 15) clearly shows after each thrust pulses a decrease in the perigee altitude. The final altitude is 550 km as expected.

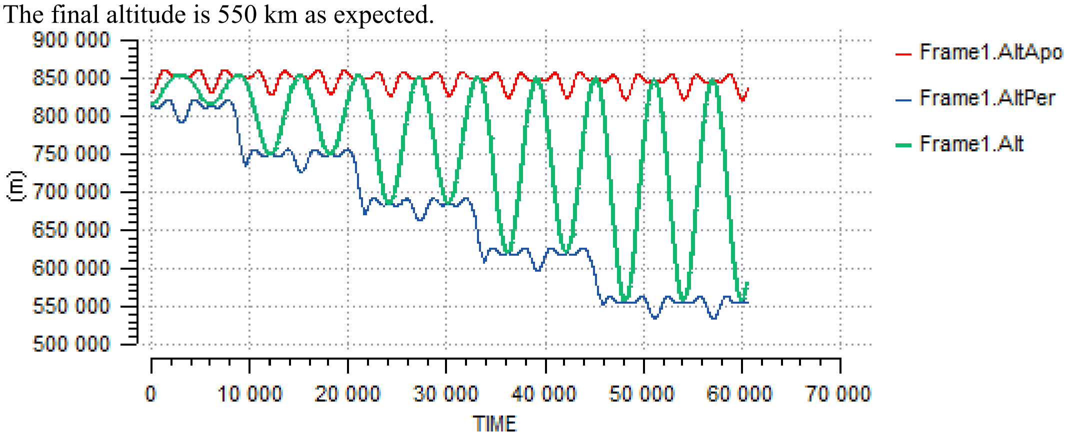

Fig. 15 Altitude and osculating orbit parameters (apogee and perigee altitude)

With a suitable 3D discretisation of the fluid into the tanks, it is possible to exhibit the Archimedes pressure at the outlet of the tanks (Fig. 16). As expected with a total thrust of 30 N over a total mass of 1800 kg, the acceleration is quite small and the absolute value of the Archimedes pressure is the order of the pascal.

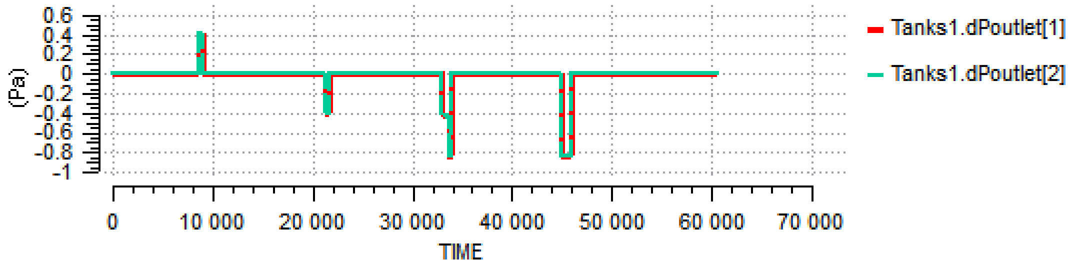

Fig. 16 Archimedes pressure at tanks outlets

An interesting output of the simulation is dealing with the dissymmetry of the centre of mass location of the fluids as shown in Fig. 17. Because the tanks axis are perpendicular to the velocity axis (X) and the thrust occur along that axis, the fluid in one of the tanks (tank n°2 placed on negative X axis) is displaced during the thrust pulse toward the +X while for the other tank (tank n°1 placed on positive X axis) the fluid stay on the most positive X location with or without thrust because of the earth pointing rotation push already the fluid in the same direction.

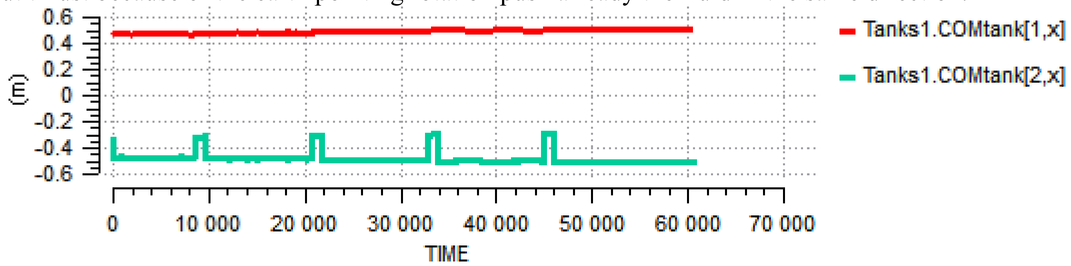

Fig. 17 Centre of mass of the fluid in the two tanks (component X, along the trust direction)

8.2. Mission cases for a GEO satellite

The second mission case is a GEO satellite with the first apogee kick motor (AKM) manoeuvre but simplified with one single pulse, Fig. 18. The satellite used for this assessment is known in the available documentation as TDF-TVSAT. The mission goal is from a geostationary transfer orbit (GTO) to reach in one thrust pulse a quasi geostationary earth orbit (GEO).

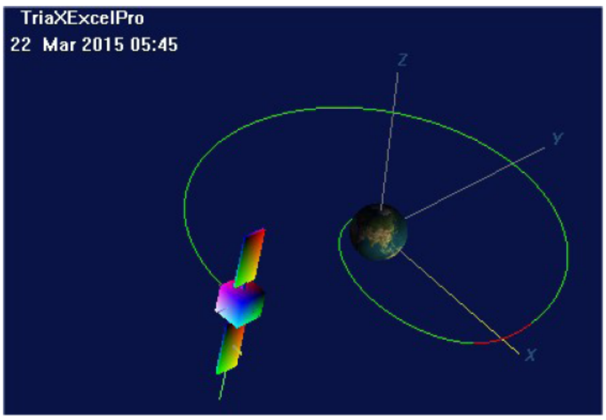

Fig. 18 GEO satellite AKM manoeuvre

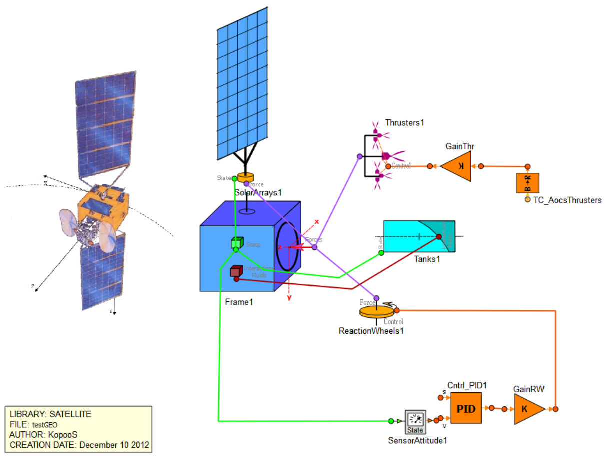

Fig. 19 GEO satellite TDF-TVSAT model

By hypothesis for this simple case, the first pointing is a Z axis (also the AKM thrust axis) Earth pointing. Thus a first pitch manoeuvre shall be performed for setting the alignment of the Z axis within the local horizontal plane: that is a rotation of 90° that is performed with RW. Then at the wanted time the thrust pulse is performed while keeping the attitude of the Z axis in the local horizontal plane. The duration of the thrust pulse is the one given by any impulsive Hohmann transfer tool. The location of the middle of the thrust pulse is the apogee of the initial GTO (with a very slight trim).

The model used in order to simulate this manoeuvre is shown in Fig. 19. The model is similar to the previous model except that in the data there are two solar arrays, and the location of the thrusters and thrust vector are updated according to the available documentation.

Several plots describe the outputs of the simulation.

The thrust vector is provided along the positive Z axis as shown in Fig. 20. The effect of the command of the RW on the satellite attitude are shown in Fig. 21

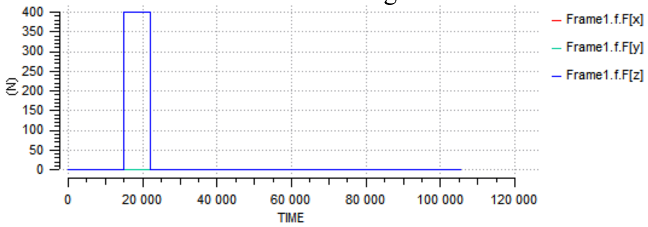

Fig. 20 Thrust pulse of AKM

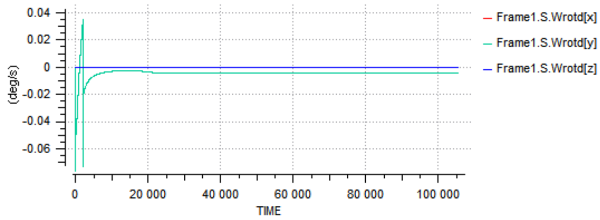

Fig. 21 Satellite rotation rate around the pitch axis Y

The altitude of the satellite is shown in Fig.22 where the quasi GEO is reached after the performance of the single thrust pulse. The Archimedes pressure at the outlet of the tanks is shown in Fig. 23, and as expected the highest pressure (120 Pa) occurs for the oxidizer at the beginning of the thrust when the height of fluid is at its maximum.

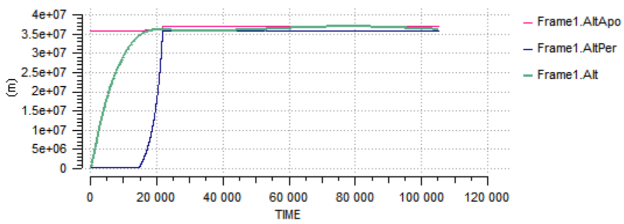

Fig. 22 Altitude and osculating orbit parameters (apogee and perigee altitude)

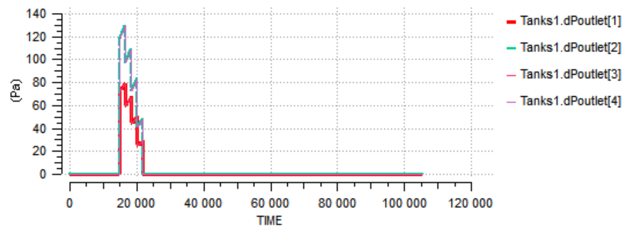

Fig. 23 Archimedes pressure at tanks outlets

The location of the centre of mass of the fluids into the tanks is shown in Fig. 24 for the component along the thrust axis (+Z) where the depletion of the tanks lead to move the COM location toward smaller location along Z.

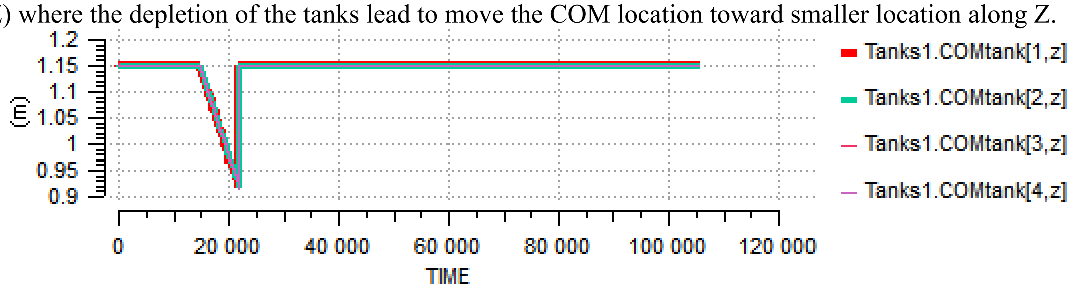

Fig. 24 Altitude and osculating orbit parameters

The full orbit transfer is better shown with a 3D visualisation tool. The Fig. 18 has been set with the outputs of the simulation results of this GEO satellite model thanks to the SATELLITE library.

9. Conclusions

The extensions for implementation in the third development phase of the European Space Propulsion System Simulation (ESPSS) have been presented. The new developed SATELLITE library has described in details with some validation cases.

Finally, a conceptual demonstration of the evolutionary behaviour models for a classical mono and bi-propellant chemical propulsion system for a LEO and for a GEO satellite have been presented including the Archimedes delta pressure induced by the thrust force and the change in location in the centre of mass of the fluids into the tanks.

The first goal of the SATELLITE library is to be able to perform simulations of the satellite's mission interactions with the propellant. As shown in the paper, the library can deliver very accurate outputs at system level.

10. Acknowledgments

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11. Nomenclature

A	Local area (m²)
$\vec{A}$	Acceleration due to non-gravity forces (m/s²)
COM	Centre of mass
$\vec{\nabla} P$	Gradient vector of the scalar P, $\left(\frac{\partial P}{\partial x} \quad \frac{\partial P}{\partial y} \quad \frac{\partial P}{\partial z}\right)^t$
ECI	Earth Centred Inertial Frame
Isp	Specific impulse (s)
P_{perturb}	Perturbing forces vector from other bodies, interaction forces (N)
P	Pressure (N/m²)
T_{thrust}	Resultant thrust vector (N)
$\vec{\Omega}$	Instantaneous rotation vector (rd/s)
g_o	Constant 9.80665 (m/s²)
m	Spacecraft mass (kg)
r	Radius vector from focus body to spacecraft (m)
r , r_S	Radius length (m)
RW	Reaction Wheels
SA	Solar Arrays
GB	Gravity booms
t	Time (s)
v	Spacecraft velocity vector (m/s)
γ	acceleration (m/s²)
$\vec{\pi}$, $\vec{\Pi}$	Global vectors
ω	Module of Ω (rd/s)
^	vector product

12. References

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[R 2] ESPSS release 3.0.

[R 3] C R. Koppel, M. De Rosa, J. Moral and J. Steelant "Effects of a Satellite Mission on the Propulsion Subsystem", SP2012 2364281 Space Propulsion 2012, 7 – 10 May 2012,Bordeaux, France

[R 4] C R. Koppel, M. De Rosa, J. Moral and J. Steelant "A Satellite Library In EcosimPro for fhe Aocs' Effects on the Propulsion Subsystem", 5TH ICATT 2012, ESA/ESTEC, Noordwijk, The Netherlands 29 May – 1 June 2012

[R 5] C R. Koppel "ESPSS SATELLITE LIBRARY", ESPSS Workshop, ESA/ESTEC, Noordwijk, The Netherlands 21 May – 23 May 2013