VEGA RACS WATERHAMMER ANALYSIS

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OVERVIEW

This paper presents a waterhammer analysis of the Reaction and Attitude Control System (RACS) of the VEGA rocket. The analysis has been carried out using Flowmaster, a 1D thermo fluid flow software package. This software has been previously validated using test data from Ariane 5 SCA waterhammer tests [1]. Values of pressure due to waterhammer when closing up to 4 flow control valves (FCVs) simultaneously have been found to be of the order of 3 to 4 times the value of the tank feeding pressure (tank feeding pressure = 26 bar).

1. INTRODUCTION

In order to provide launch services to the small payload family of satellites, Europe has committed itself to develop and built VEGA. This new launcher is compatible with payload masses ranging from 300 to 2500 kg, depending on the type and altitude of the orbit required by the customer, SSO (Sun Synchronous Orbit) or LEO (Low Earth Orbit). The benchmark for VEGA's in-orbit launch capacity is 1500 kg into a 700 km-altitude polar orbit.

This ESA Programme, having ELV as Prime Contractor for the Launch Vehicle, is expected to be finished and therefore be ready for its inaugural flight before the end of 2007. Astrium Bremen is the Subsystem's Responsible for the Reaction and Attitude Control System (abbreviated RACS).

When designing any hydraulic system it is of vital importance to know which is its behaviour against pressure surges or quick transient phenomena (as, for instance, waterhammer). Waterhammer is created by anything in the system which can change fluid velocity abruptly, such a pump stopping suddenly or a valve being closed too quickly. Any fluid flowing in a pipeline possesses kinetic energy. When its velocity is abruptly changed, this energy is converted to pressure. This pressure occurs in the form of a shock wave propagating up and down the system. High pressure peaks can mechanically damage the piping in the network and, eventually, they can provoke a complete failure of the whole system.

The maximum pressure change occurs at the location of the disturbance and is given by the Joukowsky equation:

(1) $$\Delta p = \rho a \Delta v$$

where

Δp magnitude of pressure change
ρ liquid density
a wave speed
Δv change in flow velocity

The sonic speed is calculated using the following formula:

(2) $$a = \sqrt{\frac{1}{\rho\left(\frac{1}{E_{fluid}} + \frac{D\Phi}{tE_{wall}}\right)}}$$

where

E_{fluid} Young's modulus of fluid
E_{wall} Young's modulus of pipe wall
D Inner diameter of the pipe
t Thickness of pipe wall

and $\mathbf{\Phi}$ is a number related to Poisson's ratio that takes into account the longitudinal stress in the pipe and the manner in which the pipe is held in place. It is normally assumed to take this value equal to unity.

The analysis has been carried out using a 1D thermo fluid flow software package called Flowmaster. This software has been previously validated using test data from another rocket's Attitude Control System (Ariane 5) [1].

2. MAIN ASSUMPTIONS AND SPECIFICATIONS

The goal of the present contribution is to analyse the transient behaviour of the fluid in the RACS when, for instance, suddenly closing or opening one or more of the flow control valves feeding the thrusters present in the system. Hydrazine (N_2H_4) is used as working fluid at a tank pressure value equal to 26 bar.

The following points reflect the main assumptions and specifications of the present analysis:

- Any kind of heat transfer is neglected due to the speed of the main phenomena object of study: the watehammer effect.
- All pipes are treated as elastics, i.e., they will expand and contract due to the pressure fluctuations in the fluid.
- The working pressure value is equal to 26 bar and the working temperature is equal to 16℃.
- The branching manifolds elements are modelled as discrete losses (elements situated just before the flow control valves).
- The characteristic values of the closing times of the FCVs (flow control valves) are equal to 10 ms.
- The analysis is transient and the flow is considered monophasic.
- The working fluid is hydrazine (N_2H_4). An internal fluid database is available in Flowmaster dealing with this and other fluids.

3. MODELLING

The VEGA RACS is a typical monopropellant tank pressure-fed system. Hereafter, a complete schematic of the RACS system is provided (FIG. 2). For the sake of completeness, *close-ups* of other parts of the network are also shown. The elements numbers are shown in red and the nodes numbers are in black. The network is symmetric from the divider in terms of number and type of elements (not in terms of geometry):

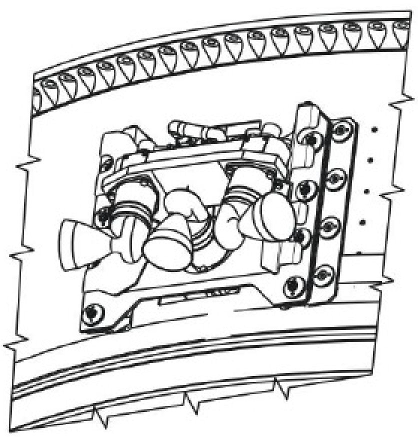


FIG 1. 3D view of one thuster cluster of the VEGA RACS

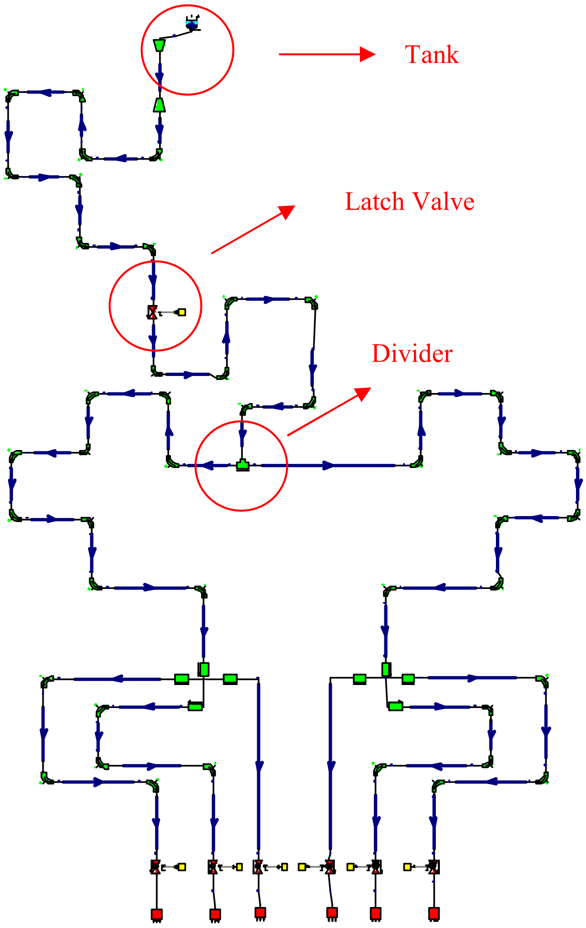


FIG 2. RACS hydraulic model (main schematic)

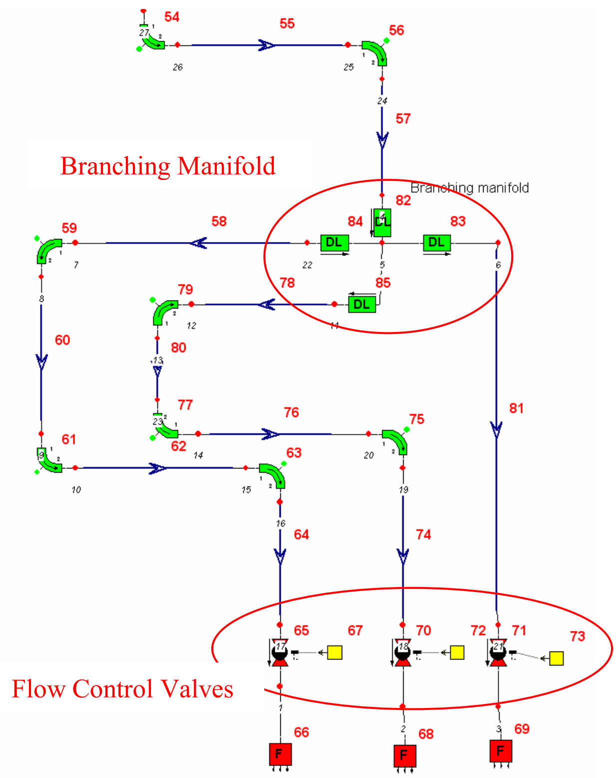


FIG 3. Thruster cluster (left side of the model)

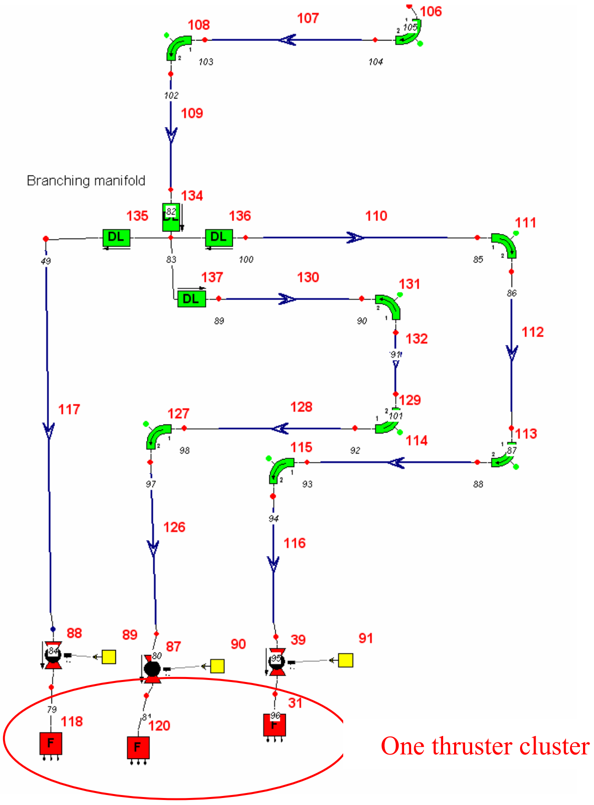
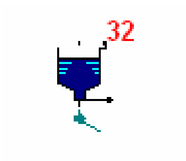


FIG 4. Thruster cluster (right side of the model)

3.1. Element description

This section gives a description of how each of the elements forming the network is modelled:

3.1.1. Tank



The level of liquid in the reservoir is calculated at a given time, taking into account the change in horizontal cross-sectional area with liquid level.
The Bernoulli equation for this element reads as follows:

$$P_s + \rho g L(t) + \rho g Z - P_1 = \frac{K \dot{m}_1 |\dot{m}_1|}{2\rho A^2} \quad (3)$$

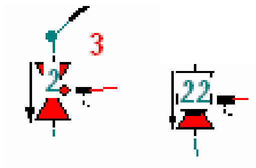
where:

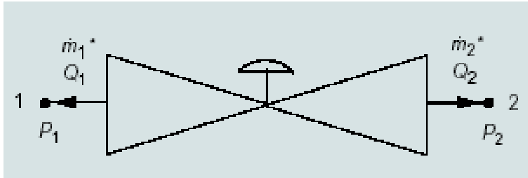
Ps = Surface pressure
ρ = Density
g = Gravitational constant
Z = Level of reservoir base above universal datum
P1 = Pressure at node 1
K = Loss coefficient (inflow or outflow)

$\dot{m}_1$ = Mass flow rate at node 1
A = Cross-sectional area of pipe/inlet
L(t) = Liquid level in reservoir at time t

3.1.2. Latch and Flow control valves

The figure below shows the main variables defining a valve, either a latch valve or a mass flow control valve.

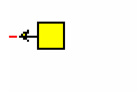




where

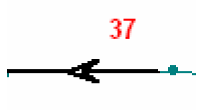
P_1 = pressure at node 1
$\dot{m}_1$ = Mass flow rate at arm 1
P_2 = pressure at node 2
$\dot{m}_2$ = Mass flow rate at arm 2
Q_1 = Volumetric flow rate at node 1
Q_2 = Volumetric flow rate at node 2

3.1.3. Controllers



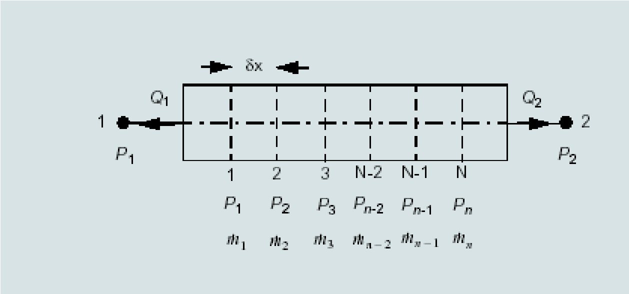
Controllers can be connected to a valve to regulate its modus operandi: they dictate when and how much the valve has to be opened or closed.

3.1.4. Pipes



Pipes are the key elements where waterhammer effects take place. Thus, a good modelling of these elements is essential for a good prediction of the pressure surges expected.

Using the method of characteristics, the pipe is divided into a number of internal reaches with a length (δx) equal to the distance travelled by a pressure wave during one time step.



Therefore the following equations apply:

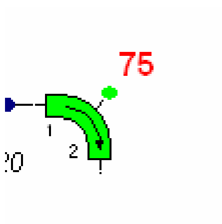
(4) $\delta x = a\,\delta t$

(5) $S = \dfrac{L}{a\,\delta t}$

where

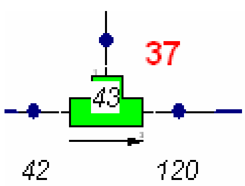
S = N + 1 = Number of internal sections
N = Number of internal nodes
L = Pipe length
a = Wave speed
δt = Timestep size

3.1.5. Bends



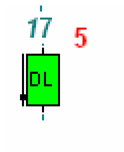
Bends are relatively low loss components. The bend loss coefficients for smooth circular bends take into account, among other factors, the arc length on the centre line. Hence the coefficients increase for large r/d T-junctions (being r the radius of the arc and d the internal diameter of the bend).

3.1.6. T-junctions



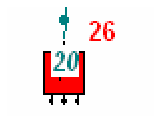
In some cases, the pressure losses that are associated with T-junctions are small when compared to the pressure losses in the rest of the network.

3.1.7. Discrete losses



Discrete losses components have been chosen to model the branching manifold. A discrete loss provides a way of modelling a pressure loss between two nodes within a system, where the only purpose of the component is to simulate a flow restriction within the system.

3.1.8. Flow sources



A flow source has been chosen to model the thrusters of the system. It supplies a constant flow rate either to or from the component, irrespective of the other conditions. The value of the mass flow for the VEGA RACS thrusters is equal to 0.097 kg/s, considering a steady state situation of a nominal thrust equal to 215 N.

3.2. Pressure losses in the system

In the piping system, the part of the total pressure which is spent in overcoming the forces of hydraulic resistance is irreversibly lost. The pressure losses in the piping system are (Darcy-Weisbach equation):

(6) $\Delta p = \zeta \dfrac{\rho \cdot u^2}{2}$

where the fluid resistance coefficient ζ is defined as the total energy loss over the dynamic pressure. It is divided into local resistance ζ_{loc} and continuous resistance (always friction) ζ_{fr}:

(7) $\zeta = \zeta_{loc} + \zeta_{fr}$

where the friction loss coefficient ζ_{fr} of an element is defined through the friction factor of hydraulics λ as:

(8) $\zeta_{fr} = \lambda \dfrac{l}{D_h}$

Here, l is the section length and Dh the hydraulic diameter. For constant hydraulic diameter, the friction factor λ is a function of the Reynolds number Re, the non-dimensional roughness (assumed non-uniform) of the channel $\overline{\Delta} = \Delta / D_h$, and of the bending parameters, if any.

In the case of valve loss coefficients, they depend on type, size and valve opening.

4. RESULTS

Transient simulations to account for the water hammer pressure surges in the piping system of the RACS network have been carried out. A temporal and a 1D spatial grid have been set. The value of the time step is Δt = 4.07734e-006 seconds. This value has been calculated using a subroutine in Flowmaster. The method takes into account all pipes lengths and outputs a time step in order to have an integer number of internal nodes at every pipe.

Following the mission profile for the attitude control of the rocket, four different analyses (scenarios) have been carried out. These are the more likely scenarios to happen during the mission:

1) Pitch control: Closing of one (1) FCV (flow control valve): valve 65

2) Roll control: Closing of two (2) FCVs simultaneously: valve 65 + valve 87

3) Pitch and roll control: Closing of three (3) FCVs simultaneously: valves 65 + 70 + 87

4) End of mission: Closing of four (4) FCVs simultaneously: valves 65 + 70 + 87 + 39

The mathematical model is run for 200 ms without any closing of the valves in order to get a stabilized situation. The Latch Valve (LV, main valve in the system, see FIG.2) is maintained opened at all times (nominal operation) and the Flow Control Valves (FCVs) that are not part of the current closing operation, remain closed during the whole simulation process. Then at t = 0.2 s the closing command of the FCV or FCVs object of study is given. The closing time was considered linear and equal to 10 ms, i.e. at t = 0.21s they were already closed (to locate the FCV/FCVs in the network, please see FIG. 3 and 4).

The pressure time evolution graphs at the inlet of the flow control valves where the waterhammer pressure value is the largest are shown for every scenario (the Y axis shows pressure values in [bar] and the X axis shows time values in seconds [s]).

4.1. Results scenario 1)

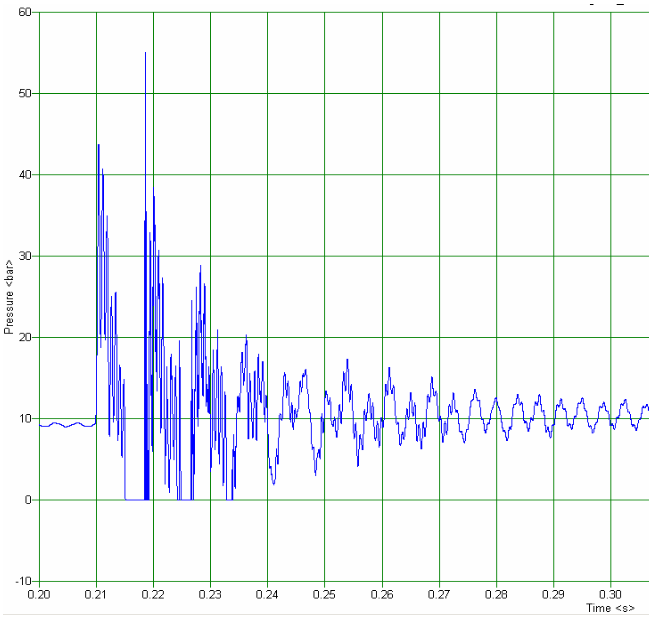


FIG 5. Inlet pressure at Valve 70

4.2. Results scenario 2)

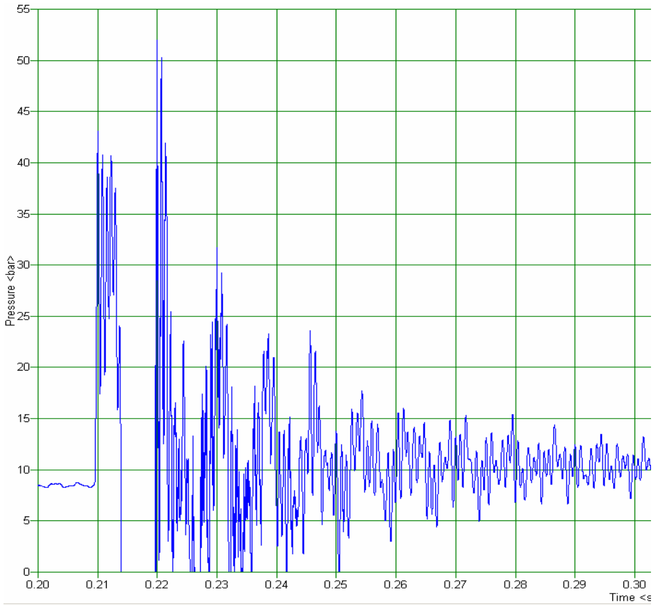


FIG 6. Inlet pressure at Valve 65

4.3. Results scenario 3)

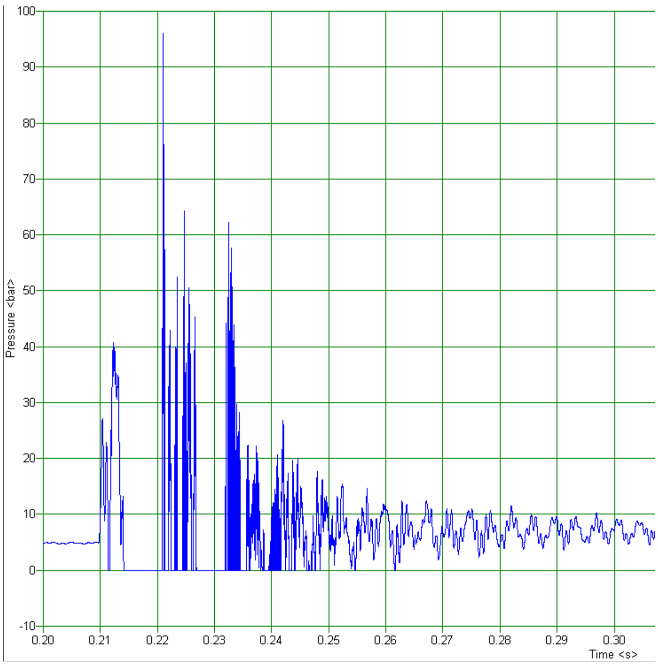


FIG 7. Inlet pressure at Valve 39

4.4. Results scenario 4)

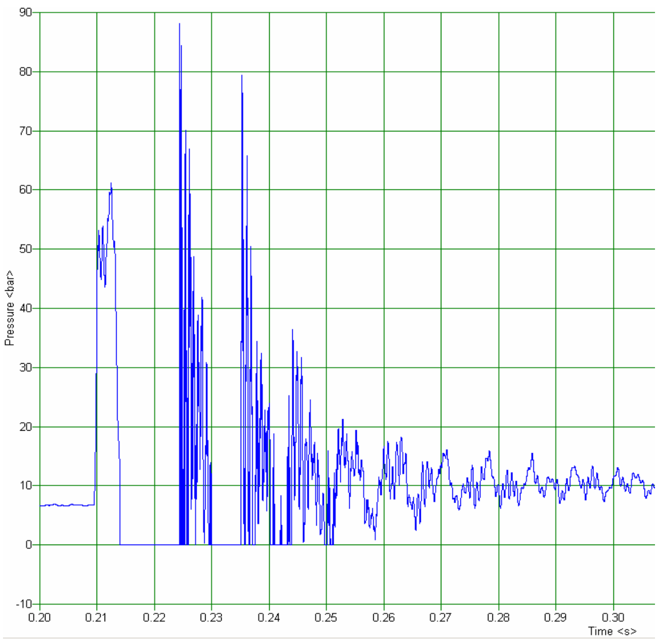


FIG 8. Inlet pressure at Valve 65

The first thing one can observe is that the curves are not very "clean": there is quite a lot of numerical dispersion. The origin of this dispersion is not completely understood. It can be linked to the solver, to the boundary conditions, etc … Similar curves were observed in [1]. Nevertheless, during the validation process, the values of the waterhammer peaks and the main frequency were well reproduced.

Another important outcome of the last plots is the value of the total pressure loss of the system: knowing that the initial pressure of the tank is equal to 26 bars and at the inlet of the valves the pressure is approximatedly equal to 8 bars, then around 18 bars are lost in the system.

5. CONCLUSIONS

The maximum value of any peak pressure value of the different cases studied does not exceed 100 bar. It goes in line with the fact that the tubing is mechanically designed to withstand a permanent pressure value of 150 bar (it is reminded that loads due to waterhammer vary in time and they only reach its maximum value during a short duration in time).

To summarize all the results obtained during this analysis, the following table is presented. In it, the maximum value of the pressure is given for each of the different scenarios studied:

	1 FCV (65)	2 FCVS (65+87)	2+1 FCVS (65+70+87)	2+2 FCVS (65+70+87+39)
FCV 65	44	50	80	87
FCV 70	55	48	70	82
FCV 71	33	37	50	58
FCV 88	24	23	37	33
FCV 87	30	33	58	65
FCV 39	50	38	95	68

TAB 1. Maximum pressure value for every scenario [bar]

As said before, there is quite a lot of numerical dispersion. The previous table shows the values of the pressure including this dispersion, because it is difficult to say where the physical value finishes and where the numerical one takes over.

These graphs have to be analysed with care: logically, closing a higher number of valves would lead to a larger value in pressure, and this is a situation that it is not always fulfilled. Reasons for this situation can be explained by the numerical dispersion or by a not completely correct modelling of some elements.

6. FUTURE WORK

Some time after the finalisation of this study, some test cases were carried out using another software named Ecosimpro. The idea was to be in possession of a tool more specialised in space propulsion. EcosimPro can account for two-phase flow waterhammer effects with a non-condensable gas phase. This software has also a comprehensive space propellants database.

A good deal of work has already performed using this code at Astrium Bremen. Reproduction of water tests on the Ariane 5 Attitude Control System (Systeme de Control d'Attitude) were successfully carried out. As a next step, a model of the VEGA RACS using EcosimPro in order to run transient simulations is underway.

7. BIBLIOGRAPHY

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