Fluidic simulations and tests of space mechanical pressure regulators

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The French Microscope mission – for which CNES is prime – aims at testing the equivalence principle of Einstein's general relativity theory in orbit. The micro-satellite (scheduled to be launched in early 2016) uses a Cold Gas Propulsion System in order to provide the drag-free environment demanded by the ONERA instrument. A Pressure Regulation Module is designed to feed the thrusters with Nitrogen. Its main function, which is achieved using a mechanical pressure regulator, is to expand the gas from storage pressure (345 barg) to thruster operating pressure (1 barg). Given the very specific thrust operating range (300 µN maximum per thruster), Nitrogen mass flow rate ranges around tens of µg/s at most. However, pressure regulators are more often used in the range of tens or hundreds of mg/s (Xenon flow for plasmic propulsion or Helium pressurization in chemical propulsion) where their behavior is therefore well-known. Thus, CNES decided to develop a model of pressure regulator in order to study its behavior at very low mass flow rates. Three different studies have been performed using the EcosimPro software as a modeling tool. First, the model of a laboratory pressure regulator has been defined taking into account non-linearities and hysteresis at low flow rates. It has been tuned using test results obtained in CNES' laboratories. Besides, a Helium pressure regulator has been modeled and its behavior during fast pressurization events correlated with experimental results. Last but not least, a model representative of CGPS flight hardware has been designed. Extensive study of its behavior has been performed through simulations and tests. The experimental results have been used to finely tune the model. These studies give evidence that CNES' pressure regulator model is able to accurately describe the functioning of different items.

Nomenclature

CNES = *Centre National d'Etudes Spatiales*
CGP(S)S = *Cold Gas Propulsion (Sub)-System*
ECM = *Electronics Control Module*
Esa = *European Space Agency*
ESPSS = *European Space Propulsion System Simulation*
FM = *Flight Model*
GDM = *Gas Distribution Module*
GOD = *Gas Opposite Drains*
HPLV = *High Pressure Latch Valve*
LPLV = *Low Pressure Latch Valve*
A_d = *diaphragm area*
A_p = *poppet area*
c_v = *friction coefficient of the pressure regulator's poppet assembly*
I_{sp} = *specific impulse*
K = *pressure regulator's spring stiffness*
m = *mass of the poppet assembly*
P_{atm} = *atmospherical pressure*
P_{up} = *inlet pressure*
P_{int} = *pressure between the two stages*
P_{sv} = *pressure in the sensing volume*

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MEOP = *Maximal Expected Operating Pressure*
MT = *Micro-Thruster*
ONERA = *Office National d'Etudes et de Recherches Aéronautiques*
PRM = *Pressure Regulation Module*
QM = *Qualification Model*
TRM = *Thruster Regulation Module*
x = *poppet displacement*
x_l = *poppet free displacement*

I. Introduction

In space, the use of cold gas is one of the simplest and most reliable way in order to create a thrust : a pressurized gas expands trough a nozzle, thus creating a force. This technology has been long used in space systems, mostly for roll and attitude control. Due to the low maximal thrusts that can be expected (up to a few Newtons) and the mediocre specific impulses (50 to 120 s), this technology is now used only for specific missions that demand thrusts within the µN. It is especially interesting for missions which need fine attitude control, drag compensation or formation flying.

In order to perform a test of the Equivalence Principle, the Microscope spacecraft – realized by CNES as prime contractor – needs to compensate in real time the fine drag exerted by the residual atmosphere. This is performed using a Cold Gas Propulsion System.

The CGPS includes a Pressure Regulation Module which main function is to deliver to the thrusters a constant pressure. This task is performed thanks to a serial redundant pressure regulator. This equipment is often used in the range of tens or hundreds of mg/s, for example in the frame of Xenon flow for plasmic propulsion or Helium pressurization in chemical propulsion. In these cases the behavior of the pressure regulator is well-known. However, in the frame of the Microscope project, the flow rate that will pass through the pressure regulator is around tens of µg/s. Within this flow rate range, the pressure regulator's behavior shows non-linearities and hysteresis.

The CGPS development plan includes several performance tests that focus closely on the pressure regulator's behavior. Understanding of this behavior at low mass flow rates is mandatory. Besides, test predictions are needed and can only be accomplished via numerical simulations. For these two reasons, fine modeling of the pressure regulator – performed with the EcosimPro software – has been performed by CNES for the past four years.

The aims of this article are first to describe the pressure regulator and why studying its behavior is important. Then, the basic equations of the pressure regulator's modeling will be briefly presented. To finish, the correlation and tuning of the model for three different components will be shown. These components are a laboratory pressure regulator, a flight-like Helium item and finally the pressure regulator that will be integrated in the Microscope spacecraft.

II. Presentation of the mission and CGPS

A. Mission

The CNES/ONERA Microscope mission aims at testing the Equivalence Principle of Einstein's general relativity theory in orbit[3,5]. The idea is to observe the free-fall motion of masses made of different materials using the Earth as a gravitational source.

The payload is developed by ONERA[4]. The micro-satellite based on CNES' Myriade product line[2] – scheduled to be launched in early 2016 – uses a Cold Gas Propulsion System in order to provide the drag-free environment demanded by the instrument. The orbit is a 700 km polar sun-synchronous and circular orbit. CNES is prime for this sub-system and Esa brings its support by procuring cold gas micro-thrusters identical to those used in the GAIA and Lisa Pathfinder spacecrafts. The thrusters are manufactured by the Italian firm Selex-ES.

B. Cold Gas Propulsion System

The aim of the Cold Gas Propulsion System is to compensate the drag created mostly by atmospheric friction and solar radiation pressure through the creation of a thrust ranging from a few to several hundreds of micro-Newtons. The performances that the CGPSS shall reach in order to carry out the mission's experiment and achieve its objectives are the following :

- MEOP : 345 bars
- Thrust : 300 µN maximum for each thruster (~ 0.6 mg/s with an Isp of 50 s)
- Total mass of gas : 16.5 kg (Nitrogen)
- Operational lifetime : 2 years

The CGPS is divided into two identical and independent Cold Gas Propulsion Sub-Systems which are located on opposite satellite walls. Each CGPSS is decomposed into four subsystems or modules (cf. Fig. 1) : the GDM (Gas Distribution Module), the PRM (Pressure Regulation Module), the ECM (Electronics Control Module) and the TRM (Thruster Regulation Module).

This article focuses on the Pressure Regulation Module. It is needed in order to provide the thrusters with a constant regulated pressure. It is composed of valves, pressure transducers and most importantly, pressure regulator.

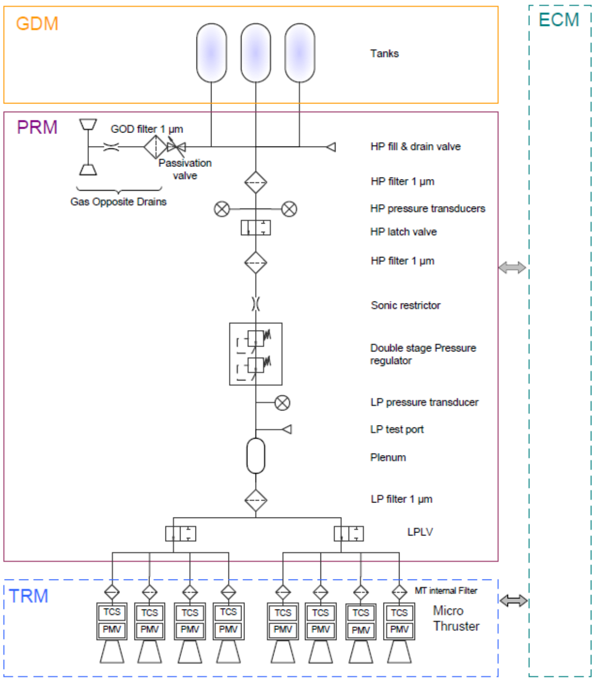

Fig. 1 : CGPSS schematic

III. Pressure Regulation Module and pressure regulator

A. Pressure Regulation Module

The Pressure Regulation Module is described on Fig. 1. It is composed of a high pressure part and a low pressure part. The high pressure part includes mainly a fill and drain valve, pressure transducers, a High Pressure Latch Valve (HPLV) and the pressure regulator. The low pressure part is composed of a pressure transducer, a test port, two Low Pressure Latch Valves (LPLV) and a plenum (~ 0.7 L capacity). The main function of the PRM is to deliver a 1 barg pressure to the TRM, i.e. thrusters, throughout the mission lifetime. This is performed by the pressure regulator, which is the junction between the high pressure part and the low pressure part. It is a mechanical device designed to deliver a regulated pressure with varying inlet pressure, temperature, outlet mass flow rate, etc. Its working principle is further described in part III - B. As presented in part II - B, the mass flow rate passing through the regulator is very low (mg/s at most but most of the time tens of µg/s).

Besides, an important secondary PRM function is to prevent the pressure rises that could occur during the mission from damaging critical equipment, e.g. the pressure regulator or thrusters. During operational phase, i.e. in stationary state, the pressure in the low pressure part is constant while the pressure in the high pressure part decreases slowly. However, during transitionary phases, slam-starts can occur in the PRM at valve opening (HPLV actuation in particular). Depending on the upstream pressure and valve orifice and downstream volume, the slam-start slope can be as high as hundredth of bar/s. If the pressure regulator is closed, slam-start will occur between the HPLV and the pressure regulator. If the pressure regulator is opened, slam-start will occur both between the HPLV and the pressure regulator and in the whole low pressure part of the CGPS. The pressure rise would thus be applied on the thrusters.

As Microscope pressure regulator does not include an anti slam-start device, two items have been added in the PRM in order to keep pressure rises at acceptable levels. These are a 60 µm sonic orifice mounted upstream of the pressure regulator and a 0.7 L capacity located in the low pressure part, i.e. the plenum.

The aim of the sonic orifice is to choke the flow and therefore limit the flow rate. Thus, no damage will be done to the equipment. The plenum is designed to increase the low pressure part volume and then lower the pressure rises.

B. Pressure regulator

Two types of pressure regulator can be used in a spacecraft : mechanical pressure regulators or electronic pressure regulators. The latter will not be discussed in this article.

Mechanical pressure regulators are mainly composed of a “poppet + seat” system, a power spring and a diaphragm. Different types of such pressure regulators exist. In the following, pressure regulators will be supposed to belong to the downstream regulated pressure type. Besides, pressure regulators will be assumed to close when the downstream pressure increases.

The basic principle of a pressure regulator is that a mechanical equilibrium exists between a spring force and a pressure force. The latter comes from the action of the outlet gas on a diaphragm.

When not submitted to pressure, the pressure regulator is in the fully opened position. When an inlet pressure is applied, the regulator will let flow the gas until outlet pressure increases and the poppet closes. The pressure regulator will stay closed if the outlet pressure stays constant. Outlet pressure will decrease if there is a mass flow rate downstream of the circuit and then the poppet will open. A steady states condition exists when the mechanical load from the spring and pneumatic load from the pressure on the diaphragm are equal.

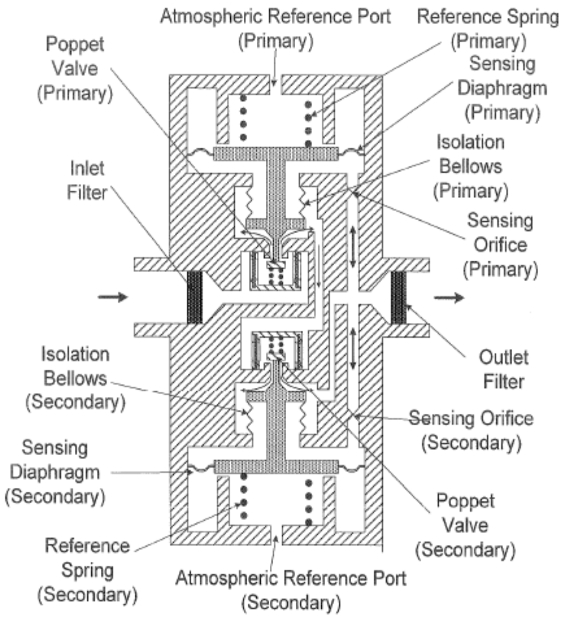

Fig. 2 : pressure regulator schematics

The pressure regulator that is used in the PRM is a serial redundant model with common sensing point (cf. Fig. 2). Its serial redundant characteristic means that only one stage of expansion is needed to expand the gas from the high pressure to its regulated value. If this primary stage fails in open position, a secondary stage is able to regulate the pressure.

The sensing point is common for both stages meaning they are regulating w.r.t. the same reference, in this case at the outlet of the pressure regulator. To prevent the regulator from amplifying oscillations coming from the outlet pressure, a small orifice separates the outlet from the sensing cavities to decorrelate the sensing pressure from the outlet pressure.

C. Why studying precisely the pressure regulator's behavior is important ?

The development plan of the CGPS has already been thoroughly presented[1]. This plan aims among other things at giving evidence that the CGPS' specified performances are met. Two major objectives related to the pressure regulator are :

- Characterization of the thruster's behavior when included in the propulsion system and more precisely, when associated with the pressure regulator (in particular cross-talk effect characterization, i.e. the capability of one thruster to perturb another).
- Characterization of the slam-start and propulsion system's capacity to withstand it.

This phenomena's characterization will be performed through simulations and tests. W.r.t. the latter, slam-start tests have been performed on the pressure regulator during acceptance testing. Besides, a breadboard model of the CGPSS has been integrated in 2013. It includes a flight-like pressure regulator and two thrusters. This equipment is mounted in a flight-like circuit and will be used to characterize the cross-talk and slam-start effects. These tests will also be performed on the whole CGPSS.

Simulations are also needed. Indeed, every test presented here above has to be simulated in order to obtain predictions and verify that the equipment will withstand the test. These simulations are performed thanks to the EcosimPro software. They include low-level simulation, i.e. at equipment level, to high-level simulation, i.e. at the whole CGPSS level. Furthermore, apart from giving test predictions, these simulations will allow close understanding of the pressure regulator's behavior.

Modeling this equipment is therefore mandatory. The first phase of the model's development has included the definition of the model's core between 2011 and 2012. Since then, validation of the model using various test results has been accomplished :

- Study of a laboratory pressure regulator and in particular the evolution of the regulated pressure vs. the mass flow rate has been performed in 2012.
- Slam-start tests on a flight Helium pressure regulator have been performed in 2012.
- Evolution of the regulated pressure vs. mass flow rate and slam-start tests has been performed since 2012 on a CGPS flight pressure regulator.

IV. Modeling and results

This chapter will focus on the pressure regulator modeling (part IV - A) and test correlations for three different pressure regulators (parts IV - B to D). The core of the model is identical for these three items. Its parameters (volume, geometry, etc.) have to be fitted for each different component.

A. Pressure regulator modeling

The software that has been used is EcosimPro. It is developed by Empresarios Agrupados Internacional with Esa funding. This software is capable of modeling dynamic systems represented by differential-algebraic equations or ordinary-differential equations and discrete events[6]. With this software, low-level equipment can be modeled in terms of thermal, fluidic, electrical, mechanical, etc. phenomena. Then, these low level items can be connected to create much complex systems. Creating specific equations is also a possibility.

The pressure regulator has been modeled using low level components such as volumes, valves, orifices and tubes. These components are pre-existing in the European Space Propulsion System Simulation (ESPSS) libraries. However, critical parts of the mechanism, such as the poppet assembly, have been specifically modeled via additional equations inside the code. The pressure regulator model is presented on Fig. 3.

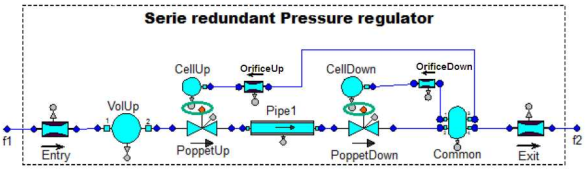

Fig. 3 : EcosimPro pressure regulator’s schematics

The geometrical characteristics of the pressure regulator will set the parameters of the orifices, volumes and tubes. The diameter of the orifices separating the common volume from the sensing volumes is particularly critical and had been empirically set as will be presented hereafter.

The poppet is seen as a mass submitted to both the spring force and the pressure force. Its movement is determined by Newton’s second law. The outlet pressure w.r.t. time will depend on the outlet volumes and mass flow that the poppet allows to go through the pressure regulator.

The poppet is submitted to the following equation:

Eq. 1 $$m \times \ddot{x} = -K \times (x - x_l) - A_d(P_{sv} - P_{atm}) - A_p(P_{up} - P_{int}) - c_v \times \dot{x}$$

x is the poppet’s displacement. The mass *m* of the poppet depends obviously on the pressure regulator’s design. The stiffness of the spring K depends on the regulated pressure and will be adapted to match its value (assuming the poppet is equilibrated i.e. its equilibrium position at lock-up pressure just touches the seat). The pressure force depends on the diaphragm area A_d which is a characteristic of the pressure regulator’s design. The poppet’s area A_p has also a small influence. To finish, a viscosity term c_v has been deemed necessary in order to stabilize the pressure regulator’s behavior as will be presented hereafter. The influence of the upstream pressure has also been taken into account in another equation that is not presented here : the regulated pressure is a function of the upstream pressure.

The “poppet + seat” assembly geometry has been arbitrarily chosen as one of the simplest and most used that is to be seen in the literature related to pressure regulators. Thus, a simple geometrical formula links the poppet displacement x to the flow area.

The set of equations governing the pressure regulator’s behavior is thus composed of the fluidic equations between the low-level components, the poppet’s movement differential equation (Eq. 1), the correlation between the upstream pressure and the regulated pressure and the geometrical relation linking the poppet displacement to the flow area. Within these assumptions, the pressure regulator’s behavior is completely reproducible and at a specific instant, does not depend on what has been applied to the component before. This means that for given inlet pressure and mass flow rate, the poppet displacement and regulated pressure are the same. Besides, if the evolution of the regulated pressure as a function of the inlet flow rate is drawn, the obtained curve will be a straight line. The pressure regulator’s would then be linear and reproducible

But, it has been observed during tests that the behavior was not linear and only reproducible when the flow rate variations (increase or decrease) were the same. Indeed, at low flow rate, the slope of the regulated pressure vs. flow rate is steeper than at higher flow rates (and is not constant). This could be due to the behavior of choked laminar flows. Indeed, as the orifice size is low, the gas speed is high and is believed to reach the choking point. But, as the orifice dimension is also very little, the Reynolds number is low and the flow is considered laminar… A thorough study of this phenomenon will not be presented in the frame of this article but would certainly be interesting.

Another reason explaining this non-linear behavior would be a “dead zone” of the poppet movement. Indeed, at very low displacements (and therefore mass flow rates), the poppet assembly could have to overcome mechanical gaps before movement is possible. As the Microscope’s pressure regulator is solely used at low mass flow rates, this effect had to be taken into account.

Furthermore, an hysteretical behavior has been observed during tests, meaning that the state of the pressure regulator at a given moment depends not only on the outlet flow rate and upstream pressure but also on the history of the previous poppet’s movement and especially if the overall poppet’s movement is currently closing or opening.

Both the non-linearity at low flow rates and the hysteretical behavior have been modeled using the same set of equations. First, the software calculates the poppet displacement x that should be obtained taking into account no non-linearity. Then, this x is replaced by $f_i(x)$. i can take two different values whether the poppet is opening or closing. This is done at each calculation step. The coefficients of these equations are empirically determined. Fig. 4 plots an example of a non-linear hysteretical movement of the poppet using these equations (the linear equation $f(x) = x$ is plotted for comparison).

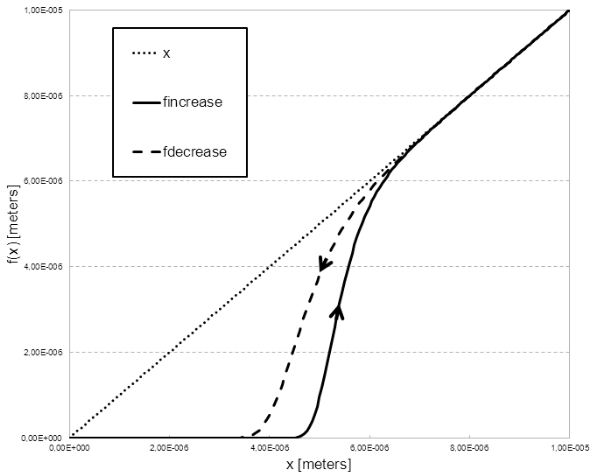

Fig. 4 : hysteretic behavior of the poppet

The equations have been determined to become linear for high values of *x*. Intermediate functions are needed in order to pass continuously from the increasing function $f_{increase}$ to the decreasing function $f_{decrease}$ but are not presented here.

To finish, it can be said that thermal transfer has been implemented in the model in order to limit the cooling of the expanded gas. The expansion of the gas is not adiabatic.

B. Laboratory pressure regulator test correlations

This laboratory equipment has been used to validate the modeling presented in part IV - A as early as possible in the development plan.

The laboratory pressure regulator is different from the flight one. It is composed of two stages but each one is used : the first one expands the gas from the upstream pressure to 35 barg and the second from 35 barg to a tunable pressure between 0 barg and 17 barg.

Geometrical characteristics have been evaluated from exploded views of the equipment. Stability assumptions (cf. part IV – C) have been made to fix parameters such as the spring stiffness.

Simple tests have been applied on this laboratory equipment (i.e. mainly applying a constant flow rate at the outlet). It has allowed plotting the regulated pressure as a function of the mass flow rate (Fig. 5, continuous curves). Hysteretical behavior can be clearly seen : the poppet is not following the same curve whether it is opening or closing.

Non-linearities are obvious too as the slope is not constant. On Fig. 5, simulation results after tuning of the parameters have also been plotted (cf. dashed curves). It shows that the model is able to predict the equipment's behavior with a good precision.

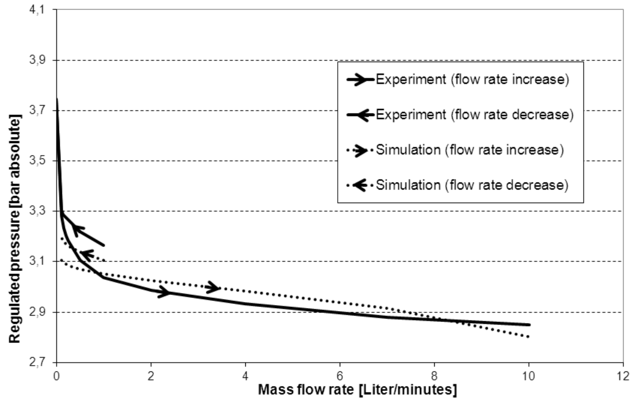

Fig. 5 : hysteretic behavior of the poppet (experiment and tests)

Moreover, the evolution of the regulated pressure w.r.t. time for a complex flow rate's profile is plotted on Fig. 6 and Fig. 7. The evolution of the pressure is plotted for experimental results (continuous curve) and so are the simulations results with no non-linearity on Fig. 6. The scales are not identical (left scale for the experimental results, right scale for the simulation). Indeed, the minimal measured pressure is lower than 3.2 barg but the simulation with no non-linearity does not decrease under a few Pascals. The model is too simplified to be accurate.

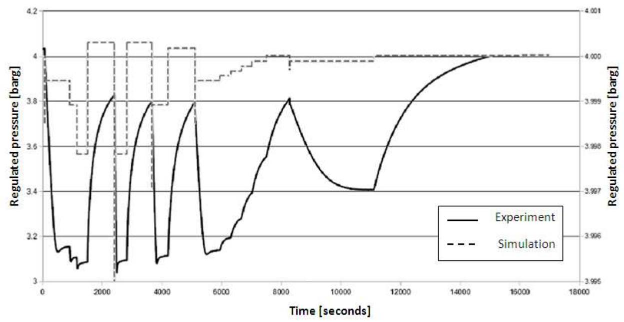

Fig. 6 : regulated pressure for complex flow rates (experiment and simulation without hysteresis or non-linearity)

In order to show clearly the improvements that are achieved adding non-linearities, Fig. 7 shows the same experimental curve (continuous curve) and the simulation result (dashed curve) obtained by adding non-linearity in the model. The improvement of the model's accuracy is obvious.

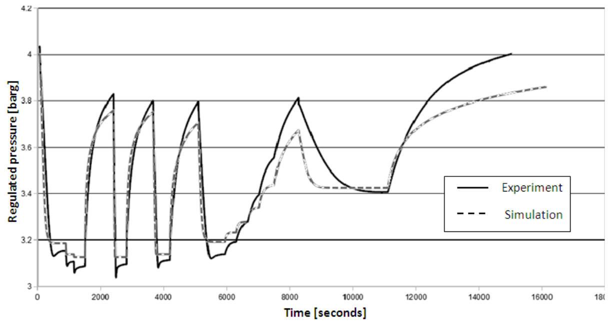

Fig. 7 : regulated pressure for complex flow rates (experiment and simulation with non-linearities)

It can be seen that when the poppet opens the correlation is better than when it closes. This could be a way to improve the model.

C. Flight pressure regulator test correlations

The fine tuning of the flight pressure regulator has been performed in three steps. The first step consists in using known characteristics of the pressure regulator to set the values of some parameters. For example, maximal mass flow rate can be used to set the maximal flow area of the pressure regulator.

The second step consists in assuming that the pressure regulator's behavior is stable. It means that for a given mass flow rate, the regulated pressure will not oscillate. The poppet displacement's equation is a major potential contributor to oscillations. This stability assumption has helped determining the value of c_v (viscous coefficient). Besides, the size of the orifice between the sensing volume and the common outlet volume has also been determined that way. The following figure (Fig. 8) shows the pressure regulator's behavior with arbitrarily chosen coefficients. The regulated pressure appears to be highly unstable. By choosing carefully the unknown parameters, it is possible to obtain a much more stable behavior.

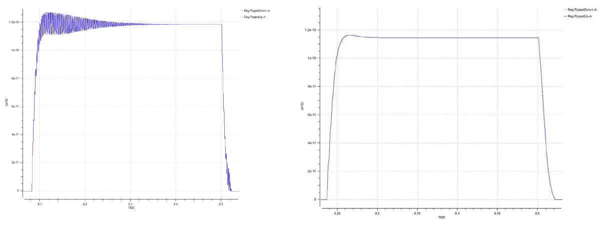

Fig. 8 : poppet position for unstable (left) and stable (right) pressure regulator

As the uncertainty on the parameters linked to the poppet movement's equation is relatively high, it has been decided to perform a sensitivity analysis. The results show that the influence of the viscous coefficient c_v is not negligible. However, the stability of the equation is more affected by the spring stiffness K. The mass m influence is comparable to the viscous coefficient's influence. Concerning the orifice size, this parameter appears to be critical. Its influence on the regulated pressure is great. As expected, if the orifice size is too important, the pressure regulator's behavior is unstable. If it is too small, the regulated pressure is submitted to great overshoots : the pressure at the outlet has too much time to increase before the sensing volume pressure is high enough to close the pressure regulator via its action on the diaphragm. Thus, the regulated pressure far exceeds the expected value. It should be noted that another critical parameter does not belong to the pressure regulator's perimeter. Indeed, the downstream volume has also a great influence, as can be easily expected.

Finally, the third step has consisted in using test results to tune the non-linear and hysteretical parameters. Furthermore, it has been utilized to check the validity of the values determined at the first and second steps. The following figure (Fig. 9) shows the regulated pressure as a function of the outlet flow rate for different upstream pressures. The non-linear behavior is shown by the variable slope of the curve. The model's ability to predict the pressure regulator's behavior is satisfactory. The low flow rates are the harder to model correctly, as can be seen.

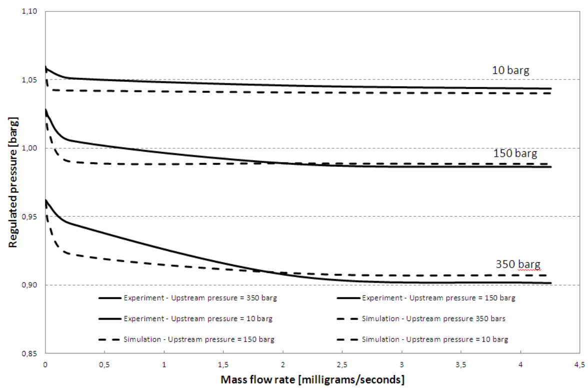

Fig. 9 : $P_{outlet} = f(\dot{m})$ (flight pressure regulator)

Slam-start test results with the pressure regulator opened have also been used. In the CGPS, a sonic orifice is mounted upstream of the pressure regulator. Its purpose is to choke the flow hence decreasing the slope of the pressure rises when the HPLV opens. Therefore, slam-start test results while the pressure regulator is closed have been used to adapt the internal volumes of the regulator. Indeed, as the flow is well-known (because it is only determined by the upstream pressure and the sonic orifice size), the only parameter that can be tuned is the internal volume of the pressure regulator (assuming all the other volumes of the circuit are known, which is the case because it is only tubing).

Slam-start test results with the regulator opened have also been used to verify that the parameters (mainly size of the poppet + seat flow area, orifice size between the common volume and sensing volume) are coherent, assuming the volume downstream of the pressure regulator is known. The following figures show a comparison between the tests and the simulations for a slam-start with the pressure regulator opened (Fig. 10). Once the downstream volumes have been re-calculated, the accuracy of the model is excellent.

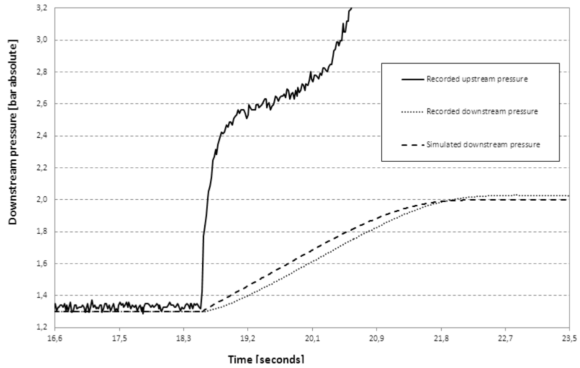

Fig. 10 : slam-start with the pressure regulator opened

D. Helium pressure regulator slam-start test results

A flight Helium pressure regulator which architecture is identical to the Microscope pressure regulator (i.e. serial redundant with common sensing point) has been modeled.

The method for tuning the component is the same than in part IV – C. A sensitivity analysis has been performed as well. Its conclusion is the same than in the previous part : one of the most critical parameter is the downstream volume.

Several characteristics of the item (regulation bandwidth and maximum mass flow rate in particular) have been determined using the model and they closely match the supplier's values that were known beforehand. This study then confirms that CNES' model is able to accurately describe reality.

To finish, slam-start tests were performed on this Helium pressure regulator after being simulated. Differences w.r.t. overpressure at the inlet of the component are minor. However, important discrepancies have been observed concerning the pressurization duration of the low pressure part. Indeed, pressurization is finished within seconds (3 s maximum) according to the simulations whereas it takes about 110 s in reality. It is believed that this disparity either comes from unknown downstream volume (e.g. in the pressure regulator) or from the size of the sonic orifice. The first hypothesis does not appear trustworthy because this unknown volume should multiply the downstream volume by a factor 30. Unknown volume can modify the results by several percents, especially if they are calculated and not measured by test, but a 30 factor is too great to be realistic. Therefore, the difference should come from the sonic orifice. This item value may have been misevaluated before the simulations. This hypothesis is confirmed by the fact that the difference between the calculated and the recorded mass flow rate is almost exactly a 30 factor.

V. Conclusion

This article has focused on the modeling of pressure regulator in the frame of CNES' Microscope project. As the CGPS' development plan is demanding a precise understanding and a good predictability of pressure regulator's behavior, a specific model has been developed by CNES. Over the years, several phenomena that appear at low mass flow rates have been taken into account, among which non-linearities and hysteresis.

The model has been used to predict the behavior of three different pressure regulators : a laboratory model, a flight Helium pressure regulator and the flight pressure regulator that will be used in the CGPS. The model is able to describe the component accurately and to predict test results with a good precision. Some discrepancies between simulations and tests have been explained and come rather from differences between the hardware and the simulations than from a flaw in the model.

Testing will now continue. Indeed, CNES will soon use the flight pressure regulator coupled with flight thrusters. The model will be used to predict this system's behavior. Besides, it will also be used to simulate the whole CGPS in order to prepare the qualification phase that shall be over within 2014.

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