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New automatic control system to improve the operation of PMD devices

TESIS

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To my family.

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New automatic control system to improve the operation of PMD devices

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In this thesis project, a functional PMD device was designed for the implementation of a control system and thus achieve a more efficient and controlled way of the propellant extraction process.
For this design process, an analysis was carried out on the different types of PMD devices and which ones could be used in a control system, as well as the selection of certain conditions of the meteosat second generation (MSG) satellite, to focus the design to something more attached to in practice.

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Nomenclature

Acronym	Definition
PMD	Propellant Management Device.
LAD	Liquid Acquisition Device.
AM	Additive manufacturing.
SC	Spacecraft.
ODEs	Ordinary differential equations.
MMH	Monomethyl Hydrazine.
MON	Mixed oxides of nitrogen.
NASA	National Aeronautics and Space Administration.
kPa	Kilo Pascal, unit of pressure.
lb_f	Pound force, unit of force.
psia	Pound force per square inch, unit of pressure.

Acronym	Definition
bar	Pressure unit.
N_2	Dinitrogen.
He	Helium.
ACS	Attitude control system.
C	Center of mass.
GTO	Geostationary transfer orbit.
GEO	Geosynchronous equatorial orbit.
SF	Safety factor.
DC	Direct current.

Symbols

Symbol	Definition
I_i	Moment of inertia in component i.
I_j	Moment of inertia in component j.
I_k	Moment of inertia in component k.
ω_i	Angular velocity about the i axis of inertia.
ω_j	Angular velocity about the j axis of inertia.
ω_k	Angular velocity about the k axis of inertia.
$\dot{\omega}_i$	Angular acceleration about the i axis of inertia.
$\dot{\omega}_j$	Angular acceleration about the j axis of inertia.
$\dot{\omega}_k$	Angular acceleration about the k axis of inertia.
ε_{ijk}	Levi-Civita density.
N_i	Component of the external momentum about the i axis.
N_j	Component of the external momentum about the j axis.
N_k	Component of the external momentum about the k axis.
S	Spin rate.
I_+	Average moment of inertia orthogonal to the rotation axis.

I_-	Measures the degree of axial asymmetry
^oC	Celsius, unit of temperature
^oF	Fahrenheit, unit temperature
K	Kelvin, unit temperature
s	Laplace operator.
ω_x	Angular velocity during maneuver, component x.
ω_y	Angular velocity during maneuver, component y.
ω_z	Angular velocity during maneuver, component z.
I_{xx}	Spacecraft's principal axes Component xx.
I_{yy}	Spacecraft's principal axes Component yy.
I_{zz}	Spacecraft's principal axes Component zz.
ψ	Angle of spacecraft's principal axes.
$[I_C]$	Inertia matrix.
H_C	Angular momentum.
g	Gravity.
σ	Surface tension.
ρ	Density.
H	Hydrostatic height.
R_2	Residual volume radius of curvature in the liquid pool on the tank wall.
R_1	Half the outer gap.
g_o	Outer gap.
Ra	Ohmic resistance of rotor windings.
La	Inductance of rotor windings.

J	Rotor moment of inertia.
B	Coefficient of viscous friction between rotor and stator.
V	System excitation source.
w	Rotor angular velocity.
T	Rotor torque.
Ea	Induced electrical voltage.
ia	System current
K_T	Field constant
K_E	Armor constant.
T_i	Friction torque, or initial torque.

Chapter 1

Introduction

Continuously and efficiently extract the propellant in a propulsion system is a very important issue. This is because an interruption in the flow or extraction could be general from a large amount of propellant remaining inside the fuel tank to a catastrophic failure in its entirety.
While on earth this is not a problem, as the presence of gravity causes the propellant to fall to a known location, in microgravity this is not the case. In the absence of gravity or low-gravity conditions, the propellant behaves in a partially indefinite manner, meaning where it will be in the tank cannot be anticipated. Another problem is the mixing of propellant with gas bubbles from the pressurized gas. However, this problem can be addressed by exploiting the prevailing force in that environment. While on earth the predominant force acting on the propeller is gravity, in low gravity conditions the predominant force is surface tension. This force acts on liquids and determines how liquids interact with solid structures. This force can be engineered by making some solid structures inside the tank that help guide the propellant to the desired location and ensure a gas-free, continuous flow of propellant to an outlet. These solid structures are called propellant management devices or PMDs.

The main goal in the design of a PMD is that it has to remain in contact with the liquid. This way, the PMD can assure flow towards the outlet. So it is always covered in liquid, regardless of the mission's phase [1].

The PMD design process starts with the evaluation of the mission requirements to determine which PMD Type are suitable. Once suitability is established, the design configuration and the design details must be explored (total volume that we introduce in the tank, added weight, dimensional characteristics and location capabilities such as propellant retention in a certain area). Finally with the design established, a thorough analytical investigation is conducted to verify performance. Mentioned above, PMD devices are usually designed specifically for each mission and tank geometry, in consequence, a large variety of PMD types exists. These types can be divided into three main groups: control devices, communication devices and the combination of these.

1.1 Motivation and Objectives

The objective is to design a PMD device and implement a control system that improves the devices currently in use. The weight is one of the parameters, but rather the most important parameter of costs in the construction of a satellite. This is due to the fact that placing an object that is too heavy in orbit entails more propulsion, in addition to being able to carry out maneuvers or missions that it has assigned. Due to this, this project will focus on two main goals:

- Reduce the volume occupied by the PMD device inside the tank. This is important because in this way two benefits can be achieved: reduce the weight of the tank with the same amount of propellant or maintain the weight of the tank, but have a greater amount of propellant, which would increase the efficiency of the system.
- Ensure with greater certainty that we can count on a complete extraction of the propellant from the tank. As mentioned before, PMD devices help with the extraction of the propellant from the tank, but currently there are still PMD devices that either extract almost all of the propellant, but occupy a lot of volume inside the tank or otherwise they are small devices but they leave remaining fuel in the tank.

  So this new device may be small, but it assures us of at least the same or greater degree of propellant extraction from the tank than a larger volume PMD.

Thus, once the project is finished, not only will a more efficient product be obtained, but it could also mark a cost reduction in the operational issue of the satellites. In addition, this PMD system may be able to better manage the extraction of propellant in unified propulsion systems. Normally, in systems with two or more propellant tanks, a variation usually occurs between the amount of propellant that is extracted from each tank, so it can generate instability in the satellite (case of the MSG satellite).

In order to achieve these objectives, it is important to know the different types of PMD that are currently found and determine which one or combination of them is best suited to this project.

1.1.1 Communication PMDs

Communication PMDs furnish a path along which propellant can flow from the propellant pool to the tank outlet and they can supply an unlimited amount of propellant in all directions [6].

These PMDs are certainly the most flexible. This category of PMD is divided into two types: the vane PMD and the gallery PMD. Galleries are the heaviest, the most costly, and, importantly, the least reliable of PMD components (but also the most capable) [1].

1.1.1.1 Vanes

Vanes are communication PMD devices because they are solid structures along the tank walls or inside it, whose function is to communicate the liquid to a specific point inside the tank.

This type of pmd device uses the change of geometry, as well as the capillarity and surface tension of the liquid in order to have a good operation [6].

A simple vane is defined as a thin solid sheet perpendicular to and traversing the boundary surface [7]. Vanes have a variety of types, each with specific characteristics and difficulties.

Figure 1.1: Vanes Types [1]

Some considerations to take into account when deciding whether or not to use this type of PMD are:

Pros	Cons
Omnidurational and omnidirectional Lightweight Less expensive Reliable	Low Flow Rates Low Accelerations

Table 1.1: Advantages and disadvantages of Vane PMDs

The uses of vanes are restricted because of their operational limits, in consequence they can't be used in bipropellant flexible demand systems. Nevertheless vane PMDs are also used in mission that requires repetitious maneuvers, like station-keeping maneuvers or one-time maneuvers. In this scenario usually control PMDs are used, such as sponges. These devices require to be refilled between the maneuvers and this task is done by the vane PMDs. This is the second main use of vane devices: refillable component systems.

1.1.1.2 Galleries

Galleries are porous element covered closed flow paths extending from the outlet to the propellant pool and are designed to communicate liquid from a pool to the outlet. The porous element prevents gas ingestion while allowing liquid acquisition [8].

Unlike vanes, galleries create a closed path or an internal path along which the propellant can flow. Indeed the typical gallery is a rectangular tunnel covered by screen on the side near the wall that follows the tank shape.

Gallery PMDs exist in a variety of configurations, as shown in figure (1.2).

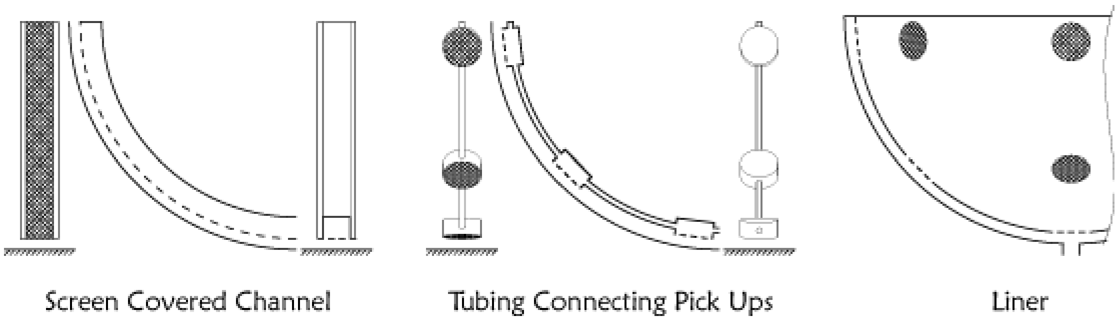


Figure 1.2: Gallery Types [1]

Gallery PMDs have some peculiarities as:

Pros	Cons
Omnidurational and omnidirectional	Heavy
Medium Acceleration	High Cost
Medium Flow Rate	High Residuals
	Low Reliability

Table 1.2: Advantages and disadvantages of Gallery PMDs

When acceleration and flow rate exceed the limit for vanes, galleries must be used. Gallery PMDs are limited by acceleration by the porous element pore size and the fluid properties. However, their acceleration limit usually doesn't prevent their use.

1.1.2 Control PMDs

Control PMDs hold part of the propellant or all of it over the tank outlet. They have limited duration capability, so they can keep propellant for repetitious maneuvers, like station-keeping maneuvers and they can be refilled between them or they can be used for one-time maneuvers, like spin recovery or a station change maneuver [6]. Devices that belong to this category: Sponges, Traps and Troughs [1].

1.1.2.1 Sponges

Sponges are control PMDs, which by definition have the main function of retaining a specific amount of propellant at the tank outlet. Having a limitation on the amount of liquid it can retain means that this device is not used for continuous maneuver missions, so its design is linked to the type of maneuvers, duration (normally short duration) and accelerations present in these.
This PMD device cannot access the full propellant reserve. As so, the main uses of sponges are [4]:

- **Ignition Systems**: In this scenario, sponges are used to hold on the outlet enough propellant to feed the pump initially, and once the ignition is done, the acceleration does the rest. Usually used for ignitions that require less than 4096,77mL.

- **Specific Demand Systems**: Specific demand systems require repeated use of a specific quantity of propellant. The most popular example is station keeping on communication satellites where burns may use 5 lbm of propellant, produce lateral acceleration on the order of 0.01 g, and occur only once every week or so.
- **Propellant Control Systems**: This envisions the idea of using a really large sponge, almost covering the whole tank, this way you can manage the propellant of the tank to be in a certain part of the pool. For instance propellant down and the gas above.

Sponges come in a variety of configurations as shown in figure (1.3).

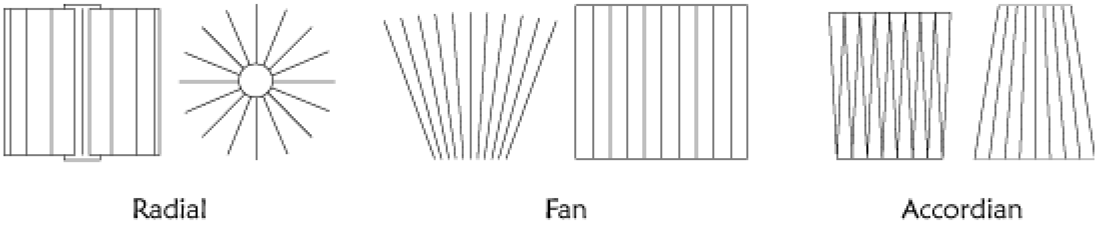


Figure 1.3: Sponge Types [1]

Some points to consider about sponges are:

Pros	Cons
Omnidirectional Lightweight Inexpensive Low Residuals Reliable	Limited Duration Burns Medium Accelerations Medium Flow Rates

Table 1.3: Advantages and disadvantages of Sponges PMDs

A fan sponge is the most efficient but is difficult to make large. The accordion is the simplest to build but the least efficient. Radial sponges are a good compromise between ease of construction and efficiency. [4]

1.1.2.2 Traps

A trap, as its name indicates, is a device or a tactic intended to capture, detect a specific objective. As opposed to sponges traps can be seen as containers or closed elements. They posses an entry window, trough which propellant can get it. Normally the window is made up of a porous element. The porous element offers propellant retention at higher accelerations than a typical sponge [9].

Some types of trap PMD are:

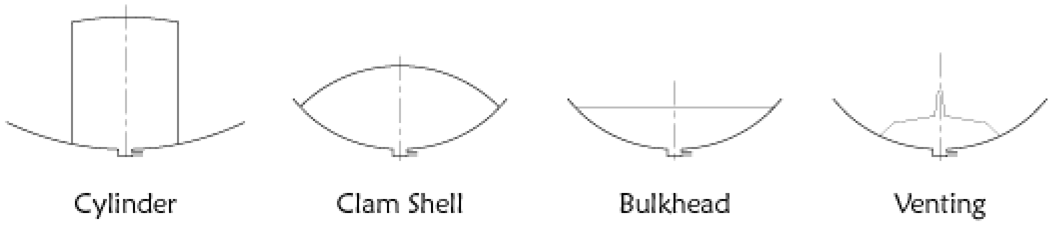


Figure 1.4: Trap Types [1]

Important characteristics of trap PMDs:

Pros	Cons
Omnidirectional Lightweight (If Small) Reliable Low Residuals	Not Passively Refillable Expensive (esp. if large)

Table 1.4: Advantages and disadvantages of Trap PMDs

Traps are not passively refillable during zero g coast like sponges. This makes them unsuitable for repeated orbital maneuvers like stationkeeping where sponges are often used. Traps are typically used for once in a lifetime maneuvers such as contingency despin, station change, or launch gas retention [6].

1.1.2.3 Troughs

Troughs are another possible control device, therefore, like sponges, they do not access the whole pool of propellant, but are capable of holding a small portion of it close to the outlet. The idea behind trough is similar to what happens when we drink coffee. The trough will be the cup that retains the coffee, in other words, it is a recipient that enforces propellant management by "enclosing it". Contrary to sponges, they do not rely on surface tension by the capillarity effect [10].

Some uses for Troughs are:

- High G Events.
- Repeated Higher G.
- Maneuvers.

Troughs come in a variety of configurations as shown in figure (1.5).

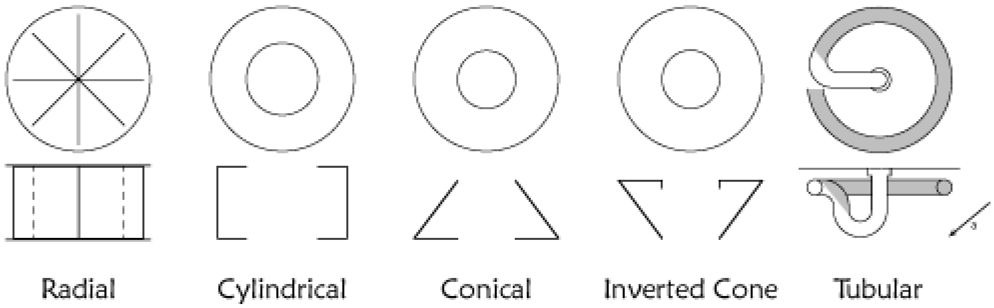


Figure 1.5: trough Types [1]

Some considerations to take into account when deciding whether to use trough PMDs are:

Pros	Cons
Very Reliable	Heavy (Except Tubular)
High G Capable	Expensive
Refillable (Except Tubular)	Limited Directionality
Low Residuals	Limited Use

Table 1.5: Advantages and disadvantages of Trough PMDs

For trough there is not much physics to cover, as we said, they are just recipients that hold material by hydro-static forces. As so, the only applicable physic is the size and form of it. Taking the cup of coffee as an example, the better closed it is, the better it will hold the propellant. Al trough it still needs to have a relatively large entry for the propellant to access. If the trough is used in combination with a vane to refill it, the size can be smaller [6].

1.2 Project proposal

Develop an automatic PMD device, which would imply that our PMD device has mobility and a control system. The project will have two parts which will be:

- Design of the PMD device (Vane and Sponge combination) according to certain parameters and delimitation to a more specific type of satellite, it will start with this combination because the sponge-type PMD needs the combination with the Vane-type PMD to make a filling at 0 g. This combination would also be ideal for being able to use a small servo motor which would provide rotation to our device, which would help to obtain better operation and location of the propellant inside the tank, because they would share the same axis of rotation.

  Once having the model of the PMD device, the automation of the device will begin, thus having the second phase of the project.

- Implementation of a control system, once located at the tank outlet, a small pressure sensor will be placed which will detect when there is variation in the outlet pressure and if there are large disturbances, it will activate the servo motor which will activate the PMD and thus to be able to achieve a better aspiration of the propellant.

Chapter 2

Project requirements

It is fundamental for the development of this automatic PMD to delimit various aspects of it, due to the fact that in such a complex device and with limited resources (due to the environment in which it is found) such as satellites. Each component has an implication in the satellite, from the weight, volume, location within the satellite and in this specific case the disturbances that may occur due to the actuator of our automatic system for the automatic PMD, because of this take a step back and having a greater overview of this project will help determine in which specific cases it is viable.

Focusing the project and design on a specific type of satellite will provide a perspective of the resources available in each case and, if possible, use their characteristics in the development of this PMD device. Taking into account that the main drawback of the development of this device is that by implementing a rotation in the PMD device this will cause a disturbance in the orientation established for the satellite. Therefore, the design must have a relevance to be able to mitigate this negative effect on the stability of the satellite.

The PMD design requirements are the flow rate and the acceleration limit that the device must withstand. All the manoeuvres and the accelerations involved in the mission must be contemplated. Considering that the design should be flexible enough in order to succeed in each potential phase of the mission. These manoeuvres are repetitive manoeuvres and the main acceleration produced by the thrusters is in the direction of the tank axis and the outlet position. Thence, it isn't a constraint for the PMD design. The adverse accelerations that should be considered are the lateral accelerations produced by the reaction wheels and the centrifugal force generated on the propellant during the rotation of the PMD. Therefore, the main requirements that must be fulfilled are:

- Main axial acceleration requirement: 2.75 g.
- PMD Angular Velocity.
- Flow rate: 2 seconds of full flow for the ignition.

2.1 Satellite type

Developing an automatic PMD device implies having a mobile device which will act when certain conditions (a variation in propellant extraction) arise in the mission, as mentioned above, the implementation of a rotation for the PMD device as part of the automatic system that will be implemented will produce a destabilization in the orientation of the satellite.

This disorientation that will occur in the satellite represents a problem in the viability of the project, because, although there will be a more efficient device in the extraction of propellant, adding a device that disorients the satellite does not seem like a great idea and a comparison begins cost-benefits between:

- Higher efficiency in propellant extraction
- Disorientation on the satellite

This disadvantage can be visualized in the equations of motion, which describe the dynamics that the satellite presents, the equations of motion are the Euler equations:

$$\left(I_i - I_j\right) \omega_i \omega_j - \sum_k \left(I_k \dot{\omega}_k - N_k\right) \varepsilon_{ijk} \tag{2.1}$$

This expression involves the Levi-Civita tensor:

$$\varepsilon_{ijk} = \begin{cases} +1 & \text{when } ijk \text{ is an even permutation} \\ 0 & \text{when there are repeated indexes} \\ -1 & \text{when } ijk \text{ is an odd permutation} \end{cases} \tag{2.2}$$

In the reference frame of the principal axes the equations of motion can be written as:

$$I_{xx}\dot{\omega}_x - \left(I_{yy} - I_{zz}\right) \omega_y \omega_z = N_x \tag{2.3}$$

$$I_{yy}\dot{\omega}_y - \left(I_{zz} - I_{xx}\right) \omega_x \omega_z = N_y \tag{2.4}$$

$$I_{zz}\dot{\omega}_z - \left(I_{xx} - I_{yy}\right) \omega_x \omega_y = N_z \tag{2.5}$$

The equations of motion are coupled, non linear, first order ODEs, if initially the spacecraft does not rotate and a torque along the x axis is applied the spacecraft rolls (rotates in the yz plane) ,the same can be said when the torque is applied along the y axis (pitch) and z axis (yaw).

Taking into account that even when the rotation of the PMD device is only on the z axis, this rotation will affect the other two axes, so the idea of implementing this automatic PMD system in a satellite categorized as not stabilized satellites arises, for example LAGEOS used to determine the geoid and to provide very accurate positions on the Earth. Due to this issue, this device will be implemented in satellites with moment bias: spinners and hybrid. Bias is defined in a loose way as the fraction of angular moment due to rotation of parts of, or all the SC.

2.1.1 Spinners Satellites

Most geostationary satellites are spinners, this specific type of satellite rotates around a revolution axis with large angular moment, due to perturbations the preceding axis is prone to nutation which can be damped. Due to gyroscopic stiffness, spin stabilization is easy, but it requires a careful design of the geometry of the satellite to ensure long term stability [10].

Spinners are characterized by maintaining constant the angular moment. For the angular velocity to be constant, it must be parallel to the angular moment. It is assumed that the rotation is exerted on the z-axis, and has a range $\omega_z = S$ [11].

Stability:

$$I_{xx}\dot{\omega}_x - \left(I_{yy} - I_{zz}\right)\omega_y S = 0 \tag{2.6}$$
$$I_{yy}\dot{\omega}_y - \left(I_{zz} - I_{xx}\right)\omega_x S = 0 \tag{2.7}$$

To guarantee long term stability I_{zz} must be maximum. Additionally, in many cases $I_{xx} = I_{yy}$. A torque perpendicular to the rotation axis is applied to move it during the operation:

$$\vec{\Omega} = \begin{bmatrix} \Omega_x \\ \Omega_y \\ 0 \end{bmatrix} \tag{2.8}$$

$$\vec{S} = \begin{bmatrix} 0 \\ 0 \\ S \end{bmatrix} \tag{2.9}$$

$$\vec{w} = \begin{bmatrix} \Omega_x \\ \Omega_y \\ S \end{bmatrix} \tag{2.10}$$

The inertia matrix $[I_C]$ referred to the coordinate axes has elements that are in general changing. If the moments of inertia referred to the spacecraft's principal axes are (I_{xx}, I_{yy}, I_{zz}) and these axes are at an angle ψ to the coordinate axes [11], where $\dot{\psi} = S$, then the inertia matrix $[I_C]$ is:

$$[I_C] = \begin{bmatrix} I_+ - I_-c & I_-s & 0 \\ I_-s & I_+ + I_-c & 0 \\ 0 & 0 & I_{zz} \end{bmatrix} \tag{2.11}$$

Where:

$$I_+ = \frac{1}{2}\left(I_{yy} + I_{xx}\right), \qquad I_- = \frac{1}{2}\left(I_{yy} - I_{xx}\right), \qquad c = cos2\psi, \qquad s = sin2\psi \tag{2.12}$$

The angular moment is thus:

$$H_C = [I_C]\omega = \begin{bmatrix} \omega_x\left(I_+ + I_- c\right) + \omega_y I_- s \\ \omega_x I_- s + \omega_y\left(I_+ + I_- c\right)) \\ S * I_{zz} \end{bmatrix} \tag{2.13}$$

Taking into account that:

$$\frac{dc}{dt} = -2Ss, \qquad \frac{ds}{dt} = 2Sc, \tag{2.14}$$

Is obtained:

$$N_x = I_+\dot{\Omega}_x + I_{zz}S\Omega_y + I_-\left[-\left(c\Omega_x - s\Omega_y\right) + 2S\left(s\Omega_x + c\Omega_y\right)\right] \tag{2.15}$$

$$N_y = I_+\dot{\Omega}_y - I_{zz}S\Omega_x + I_-\left[\left(s\Omega_x + c\Omega_y\right) + 2S\left(c\Omega_x - s\Omega_y\right)\right] \tag{2.16}$$

$$N_z = I_{zz}\dot{S}\Omega_x + I_-\left[s\Omega_x^2 + 2c\Omega_y\Omega_x - s\Omega_y^2\right] \tag{2.17}$$

A torque along the z axis modifies the spin rate:

$$\frac{dS}{dt} = \frac{N_z}{I_{zz}} \tag{2.18}$$

A torque along the x axis makes the rotation axis precede [11]. The precession rate is constant only if the moments of inertia of the x and y axes are equal:

$$\Omega_y = \frac{N_z}{I_{zz}S} \tag{2.19}$$

Once the stability of the satellite Spinners has been described, it helps to be clearer on how a reaction wheel will be implemented as an actuator for the automatic system of the controller to be implemented. Three reaction wheels will be used, one for each of the axes, but the reaction wheel corresponding to the rotary axis of the satellite will have the role of actuator in the system to be developed. This actuator will have repercussions in an increase or decrease in the rotation of the satellite, so the two reaction wheels must act to continue with the expected rotation of the satellite in general.

2.2 Propellant tank

The storage capacity of a tank and in the same way the use and missions in which it will be used is an important point to start designing and obtaining the geometric parameters of the automatic PMD device. Both characteristics are determined by several factors such as:

- Costs.
- General dimensions of the satellite.
- Main purpose of the satellite.
- Life time.

For the reasons mentioned above, it will be decided to select the characteristics that are used in the propulsion tank of a satellite categorized as spinner, the meteosat series of satellites are geostationary meteorological satellites, the second generation more specifically, The MSG satellites are 3.2 m in diameter and 2.4 m high and spin anti-clockwise at 100 RPM at an altitude of 36,000 km. accelerations it allows. (those that a standard in the market allows).

Some of the characteristics of a propellant tank for spinstabilized satellite are:

Tank Net Volume	218 Litres $2.18*10^8\ mm^3$
Propellants	MMH
Pressurant Gas	Helium (He) or Dinitrogen (N_2)
Geometrical Shape	Spherical
Maximum Expected Operating Pressure (MEOP)	22.0 bar
Proof Pressure (1.25 x MEOP)	27.5 bar
Burst Pressure (1.5 x MEOP)	33.0 bar
The Tank may be equipped with an add-on Propellant Gauging Sensor	
Interface Fixation	3 Suspension Tabs for Equatorial Load Introduction
Materials	
Pressure Vassel	Ti6AI4V STA(3.7164.7)
Suspension/Ports	Ti6AI4V (3.7164.1)
Tank Mass	11 kg
Life time	7 years
Mass Flow Rate	$135\frac{g}{s}$

Table 2.1: Propellant tank for spinstabilized satellited

The meteosat second generation it has a unified propulsion system composed of 4 propellant tanks and two pressurizing tanks, this system is designed for geostationary meteorological satellites and generates a thrust of 400 N (11 g maximum), the total weight of the MSG is about 2040 kg. As indicated in figure 2.1 four spherical propellant tanks (modified GALILEO tanks) are installed around the conical tube of the service module in a 90° angular distance. Two opposite tanks contain the same propellant in order to balance the spinning satellite [12].

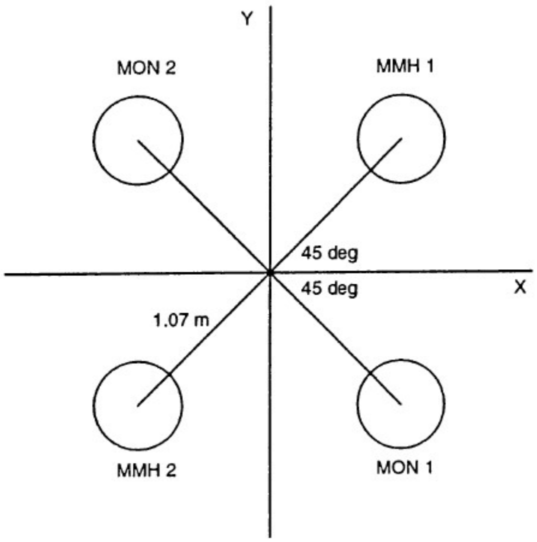


Figure 2.1: Propellant tank distribution [2]

Special provisions for equal propellant consumption from the individual tanks (i.e. orifices) will only be introduced if parallel propellant expulsion cannot be optimized by passive control of propellant migration between tank pairs. This is of high importance and one of the major UPS constraints to avoid satellite wobble by shifting the spin axis due to propellant consumption. Implementing this new automatic control system in theory would accurately control the extraction of propellant from the unified system of 4 tanks, consequently maintaining a better weight distribution in the satellite.

Figure 2.2: Selected propellant tank [3]

2.3 Propellant properties

Methylhydrazine, also known as monomethylhydrazine (MMH) has been considered in propulsion trade studies for NASA science mission concepts. A propulsion system using this bi-propellant combination will be capable of operating at a lower temperature as compared to traditional MON-3/MMH for heater power reduction [13].

Propulsion system designs and engine test programs for MMH have been carried outsince 2008. Some interesting properties of this propellant are:

Chemical formula	CH_3NHNH_2
Molar mass	46.073$\frac{g}{mol}$
Appearance	Fuming, colourless liquid
Density	875 $\frac{mg}{mL}$ (at 20 ^oC)
Melting point	-52^oC ;-62 ^oF ; 221 K
Boiling point	87.50 ^oC; 189.50 ^oF ; 360.65 K
Vapor pressure	5.00 kPa (at 20 ^oC)
Surface Tension	33.83 $\frac{dynes}{cm}$, 0.03383 $\frac{N}{m}$

Table 2.2: CH_3NHNH_2 properties

Exponential increase in viscosity of MMH when reducing in temperature below 0^oC [32^oF] poses a unique challenging in propulsion system and engine designs. A way of overcoming these disadvantages is to operate the system at optimal pressure and to limit the temperature, particularly at the low end of the temperature [13].

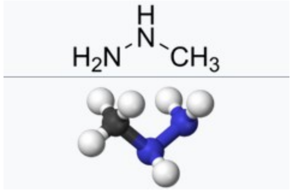


Figure 2.3: CH_3NHNH_2

Once the previous parameters have been defined, the next phase is the selection and geometry design of the PMD device that will be used in the automatic control system.

Chapter 3

PMD Design

As mentioned in Chapter 1 of this thesis, there is currently a wide list of different types of PMD devices, which have different configurations, as well as advantages and disadvantages depending on their implementation in the different missions in which that they are required.

The project design is to develop an automatic PMD device, so the PMD must be Omnidurational and omnidirectional, it must be capable of providing the correct extraction of the propellant when the automatic system is activated, this condition guides the design of the PMD by one of the PMDs categorized as control PMDs (Sponges, Traps, Troughs). As can be seen in table1.3, tables 1.4 and table 1.5 of chapter 1, these types ensure having a certain amount of propellant at the tank outlet, an essential requirement for this project because in this way, when a maneuver is required, the propellant It is already in the necessary quantity and in the exit area for its extraction, in this way time is not wasted when activating the actuator rotation and waiting for the propellant Inside to go to the area inside the tank where it is find the exit. In addition, a sensor will be implemented in that exit area to detect that it will always have propellant there, otherwise it will activate the PMD to fill this control PMD.

Defined that a control PMD is needed, Trap PMDs are discarded, as described in table 1.4, they are not passively refillable devices, so they do not fit with the demands of the project, in addition to the fact that they involve a greater expense in their manufacture. On the other hand, Troughs type are dismissed, as described in table 1.5 for being limited directionality and expensive. Therefore, the Sponge type PMDs are the most apt to be able to carry the project, due to being omnidirectional and limited duration burns, as well as their ability to be refilled between maneuvers. Most PMDs are built from components of different types. This is because one component may fulfill one mission objective and another component a second objective. For example, a repeatable spin retrieve might require a sponge and unlimited side thruster shots might require Vanes. Therefore, a Sponge and Vane PMD would be the optimal solution for both of these mission objectives. It was also considered to implement a Galleries type PMD but Galleries may need a Trap to trap the gas ingested during launch and as mentioned, it is not an option for the project, so a Sponge-Galleries combination would have inefficiencies due to interaction between both types.

The big majority of PMDs in use are employed for the ignition maneuvers where the thrust generated is in the same axis (in opposite direction) of the outlet. Thus the acceleration generated once the engine is running will make the propellant flow in the intended direction. This is used in rocket upper stages, where tanks are cylindrical or spherical.

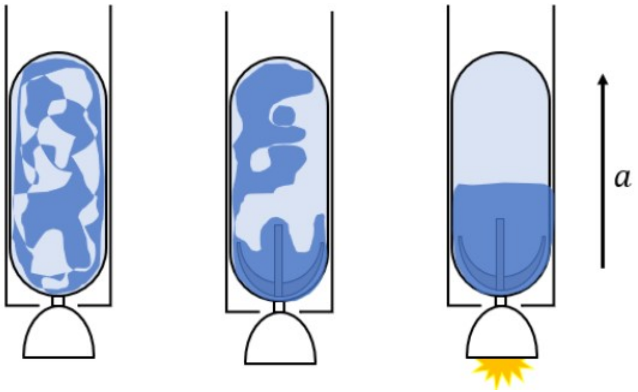


Figure 3.1: Example of upper stage without and with a PMD in micro gravity and in acceleration regime.

This configuration greatly simplifies the problem, because once the thrust is activated the generated acceleration naturally moves the flow to the outlet, so it is not necessary to activate the PMD system, it is worth mentioning that in this main ignition which will position the satellite from GTO to GEO, which would mean spending 83% of the total amount of propellant, thus resulting in 11% of the propellant for tilt control, 4% east/west manoevers and 2% the spin-rate and attitude maneuvers. Other accelerations must still be considered, such as the ones produced by the AOCS system (acceleration wheels) of the satellite, which will be much smaller than $1N$. Those adverse accelerations are expected to be in the order of 0.001g [2]. However, this automatic PMD system has another difficulty to deal with, which will be the centripetal force that will be generated when rotating the PMD once the system is active, it is at this point where the surface tension of the propellant (MMH) selected takes an important roll. It will be extremely important to correctly design the sponge to be used so as not to break said surface tension.

3.1 Sponge Design

The required PMD will be a sponge capable of holding enough propellant to start up the engine, and a simple vane system to refill the sponge when the engine is stopped. As so, the most important point of focus in this design is the sponge. The vane must be added to refill the sponge, but the expected performance and analysis to be done is less critical, as the acceleration level will be really small. In consequence, a single vane was implemented, which will have the function of sweeping the interior of the tank and recharging the sponge at the outlet.

After ignition, the propellant is settled over the outlet and the sponge must allow flow to reach the outlet. The sponge only functions to reduce or eliminate surface dip and vortexing.

Since ignition system flow rates generally are high, the propellant access window is large and located under the sponge. Once the burn ends, the sponge must hold propellant against adverse accelerations in order to be ready for the next engine ignition [4].

Sponge design is determined by setting the amount of propellant needed to meet demand. Typically, a factor of safety of two is applied to the volume. So, the first parameter to evaluate is the amount of propellant that the sponge must contain to start the ignition. The requirement to start the ignition is to make sure 2 seconds of full flow at the beginning of life.

The sponge must hold an additionally amount of propellant necessary to feed the thruster while the rest of the propellant reaches the outlet. We added the time necessary for the propellant to reach the sponge and the outlet in the worst case, when the propellant is all in the opposite part of the tank, assuming the initial velocity is null.

Using the general formula relating the traveled time to the distance, velocity and acceleration, we can obtain the time it takes for the fuel to reach the outlet from the other side of the tank.

$$\Delta x = vt + \frac{a}{2}t^2 \tag{3.1}$$

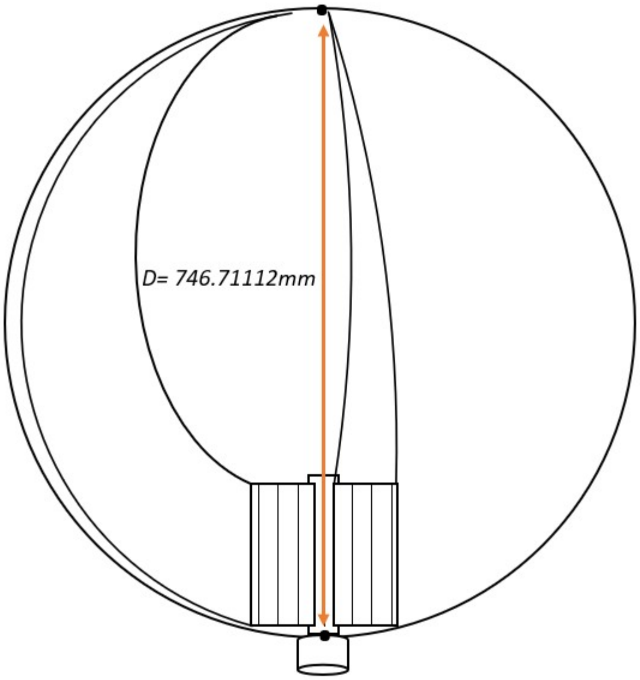


Figure 3.2: Initial design.

Obtaining t with the initial velocity condition equal to zero:

$$t = \sqrt{\frac{2\Delta x}{a_x}} = \sqrt{\frac{2D}{a}} = 2.76032\ s \tag{3.2}$$

Where Δx, the distance in the worst case position of the fuel, is the diameter D of the tank. a_x is the main acceleration in the direction perpendicular to the tank axis, in which the fuel flows along Δx. The resulting total time of full flow at the beginning of life is:

$$t = t_{ignition} + t_{additional} = 4.76032\ s \tag{3.3}$$

We overestimate the amount of propellant considering a safety factor of 2, to be conservative. Then, considering a flow rate Q at the beginning of life equal to 135 g/s, the propellant mass is:

$$M_{propellant} = Q * t * SF = 1285.281\ g \tag{3.4}$$

Finally, from the mass and the density of the propellant we can estimate the volume that the sponge needs to hold during the startup. This is done to make sure that once the full volume is consumed, new fuel arrives:

$$V = \frac{M_{propellant}}{\rho_{propellant}} = 1468892\ mm^3 = 1.468892L \tag{3.5}$$

Now that the sponge volume is decided, a further look into the shape and dimension can be done. The most general shape is a radial sponge. Now that the shape is defined, a further approach to size the sponge can be done. This will be done by iterating over the variables that define the sponge, to end up with one that meets all the requirements.

Once the amount of propellant that the sponge must hold for correct operation in maneuvers has been established, the dimensions of the sponge are determined. The sizing process is iterative. First a sponge's dimensions are assumed then the deliverable area determined. With the deliverable area known, the required sponge height can be computed. If the height is unacceptable, new dimensions are assumed and the process repeated. Sponges should not be allowed to be too high if the access window is located under the sponge as this will result in large sponge propellant residuals [4]. On the other hand, the radius of the base of the sponge is delimited to the geometric dimensions of the propellant tank, the larger this radius, the higher the position of the sponge as well as moving the entire sponge away from the outlet, generating inefficiencies in the system.

3.1.1 Sponge location relative to other components

In addition to analyzing propellant holding by the sponge, the position of the gas bubble must be addressed by examining the position of the sponge panel edges in relationship to the tank wall. First, a taper should exist between the tank wall and the panel edge to force the bubble to the preferred location. Second, the distance from the panel edge to the tank wall must be large enough to ensure that the gas bubble will not break up into smaller bubbles that are more difficult to center.

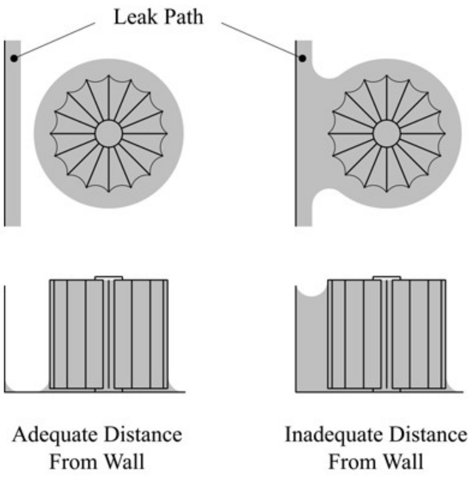


Figure 3.3: Sponge Distance to Leak Path [4].

To avoid the problem of interaction between the PMD device and the tank walls, a work zone is delimited inside the tank which is located at a distance of 2.5 cm (1 in, usually used) from the tank walls, figure 3.4, starting from this distance the sponge can be placed.

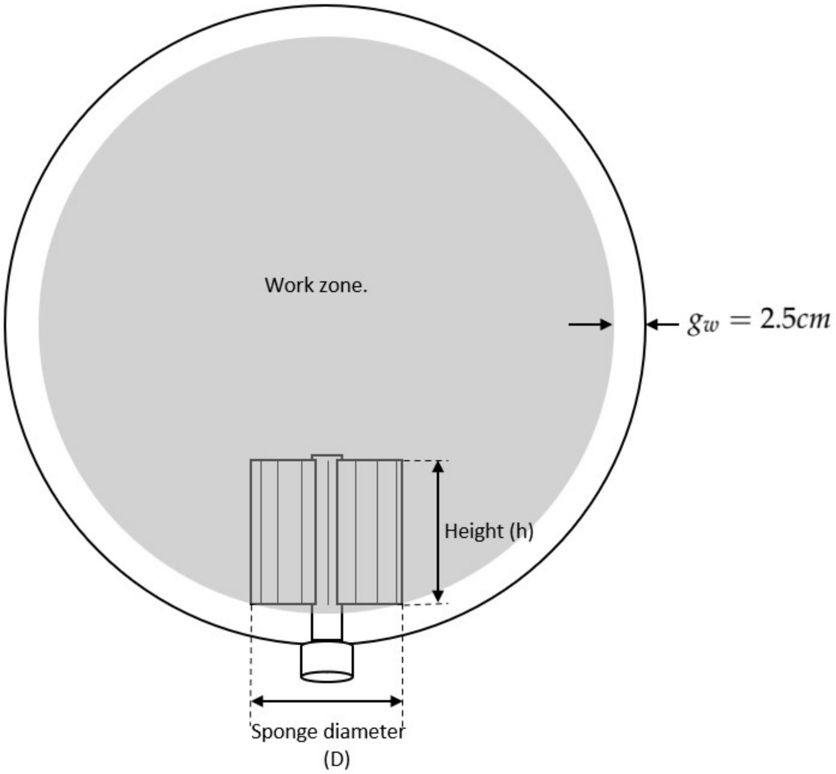


Figure 3.4: Sponge Location.

The sponge grows in size, the number of panels must be reduced to keep the mass reasonable. Thus the lateral holding capability is much lower than smaller sponges.

3.1.2 Feasibility and conceptual development

The acceleration limit of the sponge will determine the feasibility of the project. This acceleration limit must be greater than the lateral acceleration (adverse accelerations) experienced by the PMD device. The accelerations produced by the AOCS system (reaction wheels) of a SC, which will be much smaller than $1N$. Those adverse accelerations are expected to be in the order of 0.001g. Secondly, the lateral or adverse accelerations are less than 0.007 g in bipropellant systems. Therefore, an acceleration limit much greater than 0.007 g, this is considered for the design of this PMD device. Analyzing the design feasibility from the acceleration limit, using the following formula 3.6:

$$a_{limit} = \frac{\sigma}{\rho H}(\frac{1}{R_1} - \frac{1}{R_2}) \tag{3.6}$$

Where σ is the surface tension, ρ is the propellant density, H is the hydrostatic height that is the distance from the furthest point in the sponge to the opposite tank wall where liquid tents to pool, R_2 dictates the residual volume radius of curvature in the liquid pool on the tank wall and R_1 is half the outer gap.

To estimate R_2 it is assumed a residual volume equal to 0.3% of the total propellant volume:

$$R_2 = \sqrt[3]{\frac{0.003 * 3 * V}{4\pi}} = 53.84719020mm \tag{3.7}$$

Due to the configuration of the tank, the furthest point from the sponge is the distance of the tank diameter minus the height of the sponge, H=646.7112 mm and $a_{limit} = 0.007g = 0.686\frac{m}{s^2}$. Considering h=100mm and r=68.3785mm.

Isolating R_1 gives:

$$R_1 = \frac{R_2\sigma}{a_{limit}\rho H R_2 + \sigma} = 0.857604mm \tag{3.8}$$

Considering that R_1 is half of the external gap (g_o) of the sponge:

$$g_o = 2R_1 = 1.715208mm \tag{3.9}$$

Placing panels closer than 1.016 mm (0.04 inches) with an accurate and consistent gap is quite difficult and should not considered. In many cases even 1.016 mm is too close for optimal sponge mass [4]. The calculated g_o (1.715208 mm) is sufficiently greater than 1.016 mm, which would be considered as a limit for the manufacturing process, so it marks a good path in this design process. If the gaps are too large, most of the propellant in the sponge will leak, causing the sponge mass to be used inefficiently. On the other hand, if the sponge gaps are too small, manufacturing will be difficult and/or the sponge metal will occupy a majority of the sponge volume-using mass inefficiently.

As can be seen in figure 3.5, up to this point most of the geometric parameters are available, the next step is to calculate the total number of panels (N) that will make up the sponge.

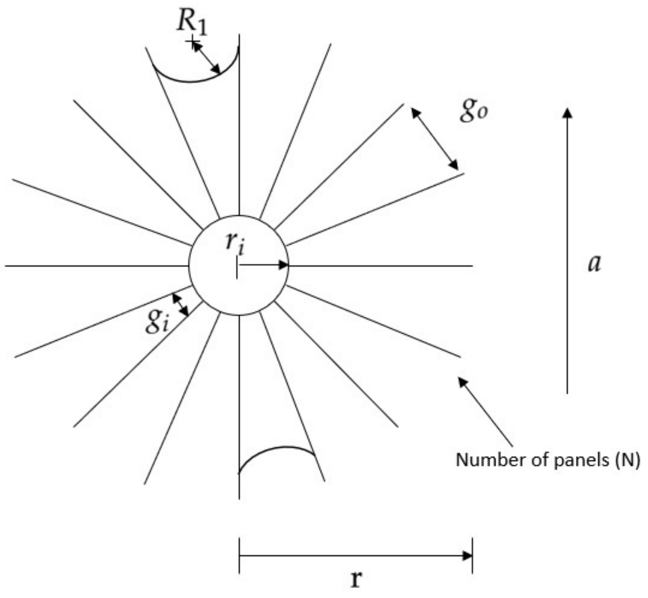


Figure 3.5: Sponge parameters in top view.

Starting from the fact that there is a radius of 68.3785 mm, there is a base perimeter of 428.6347865 mm. To know the number of panels, formula 3.10 is used:

$$N = \frac{r}{g_o p} = 224.32 \tag{3.10}$$

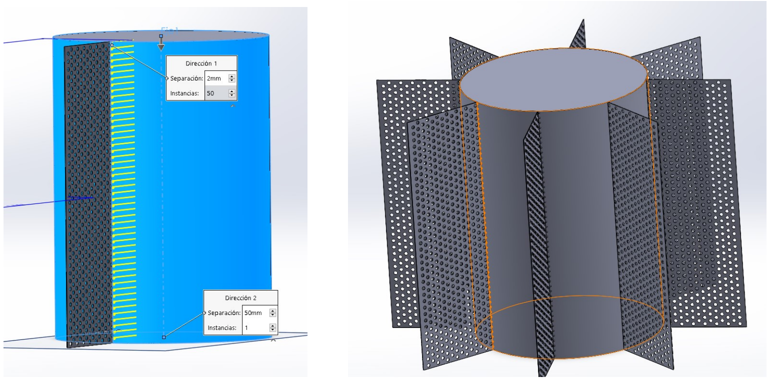
Where p is the thickness of the panel, you need to limit the thickness of the panel, 0.2 mm is a suitable thickness, because the minimum thickness for micro additive manufacturing ranges from 0.02 mm to 0.5 mm. So to end up with a sufficient strong PMD and a certain safety factor, 0.2 mm seems like a good choice. Therefore a total of 225 panels is calculated. For the interior radius of the sponge, there are a total of 225 panels of 0.2 mm thickness, so they will occupy 45mm of the interior perimeter, taking a g_i of approximately 0.8 mm plus the thickness of 0.2 mm multiplied by the 225 panels must be have a perimeter of 225 mm, so the internal radius is:

$$r_i = \frac{225mm}{2\pi} = 38.08098mm \tag{3.11}$$

To accommodate cross flow, the panels must be perforated. Generally, the perforations are relatively large and are produced by chemical or mechanical machining. A typical pattern may include 1.27 mm (0.050 inch) diameter holes spaced on 2.24 mm (0.100 inch) centers on a 60 ^{o} array. This pattern produces roughly a 20% open area which is usually sufficient for cross flow [4].

3.2 Computer Aided Design

For the development of the CAD design of the sponge, the geometrical parameters previously calculated in this chapter were considered, as shown in figure 3.6, the design process included making the same holes contained in the sponge panels but in the central cylinder between the openings of each panel.



Dirección 1
Separación: 2mm
Instancias: 50

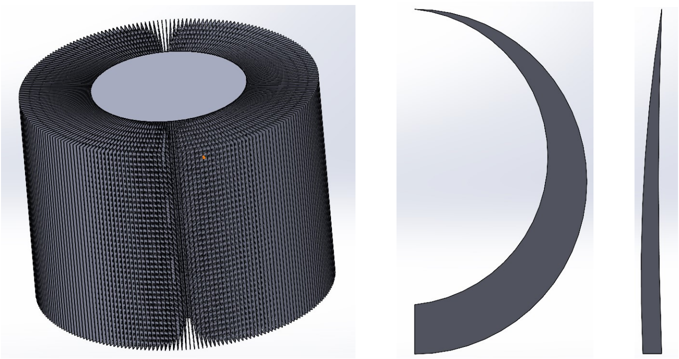
Dirección 2
Separación: 50mm
Instancias: 1

(a) Connecting holes to the central duct.

(b) Sponge preview

Figure 3.6: Relevant steps in PMD design.

Now that all that the sizing of the sponge is done, the modelling can be done in SolidWorks. The complete CAD model, sponge and two different vanes were designed in three parts, then assembled to form the final design of the PMD.



(a) CAD sponge design.

(b) CAD model vane 1

(c) CAD model vane 2

Figure 3.7: Relevant components of the PMD.

The vane is connected to the central panel of the sponge and descends in height until it reaches the other side of the tank. There should also be a small gap between the vane and the tank wall, 2.5 cm. Both vanes were placed opposite each other because placing them on the same vane could cause surface tension interference between them. Assembling everything together results in the complete design shown in the figure below.

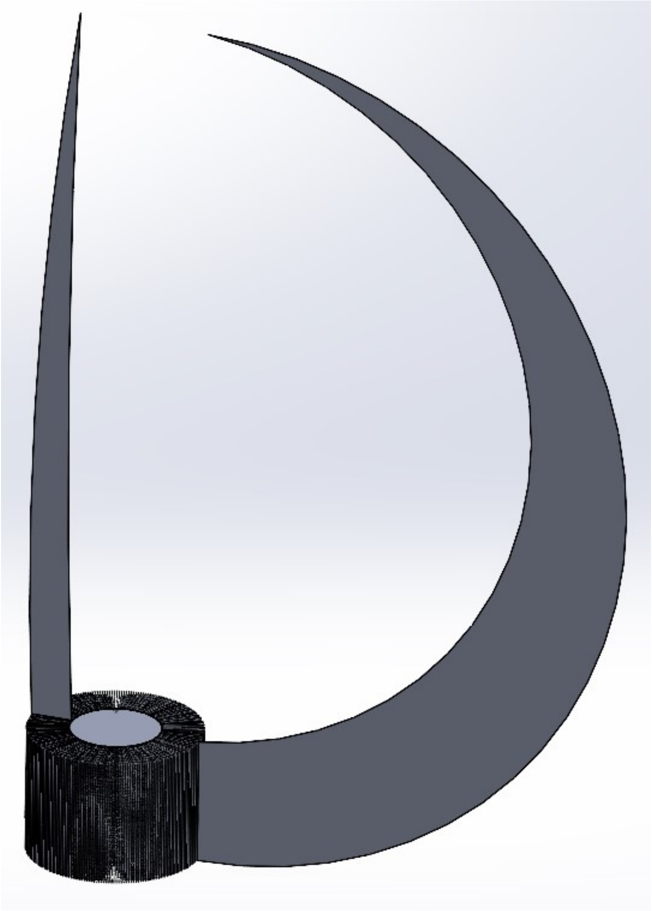


Figure 3.8: Final PMD design.

The unusual and different design of both vanes used in the final design is due to the fact that at the beginning it was planned to use a single vane which would be in charge of performing a complete sweep inside the tank by means of the rotation of the actuator. The issue with this is that the central part of the tank would have a larger surface area than the height of the sponge (due to the spherical shape of the tank), so the propellant would not be directed correctly to the sponge, it would tend to stagnate in the middle part of the tank, far away from the sponge point. In other words, for a vane to redirect the propellant to a specific point, the widest part of the vane must be located at the point of interest.

3.3 Performance

Once the design is completed, some of the physical parameters of the final design can be identified, physical parameters such as, total volume, mass as well as surface area are helpful to compare the design and whether it can become feasible. Table 3.1 describes some of the physical parameters of the final model.

Mass	1319.28 g
Volume	1319276.08 mm^3
Surface area	13308490.90 mm^2
Center of mass	X = 4.44 mm Y = 10.86 mm Z = 137.84 mm

Table 3.1: Physical parameters

It is complicated to compare the performance of two different PMD devices, because normally when changing configuration its physical parameters of course change 360 degrees. In order to make a more equitable comparison, it was considered the same configuration of the PMD designed during this work, but considering its characteristics as a static device, which would be to add 3 vane model 1, around the sponge. Table 3.2 shows only the characteristics of the Vane model 1.

Volume	13521.06 mm^3
Surface area	135625.71 mm^2

Table 3.2: Physical parameters (Vane model 1)

The performance of the PMD device with or without automatic system is described in Table 3.3, it can be seen that the PMD device with a control system obtains a reduction of the total volume of the PMD of 2.98 % and a reduction of the surface area of 2.96 %.

Volume	1319276.08 mm^3
Surface area	13308490.90 mm^2
Volume (PMD without control system)	1359839.26 mm^3
Surface area (PMD without control system)	13715368.03 mm^2

Table 3.3: Performance between PMD with and without control system.

It seems obvious that a reduction in these parameters would be obtained, which help to reduce the volume occupied by the device inside the tank. Likewise, it is clear that, although the volume has been reduced, which improves performance, it does not represent a great change because the sponge is the component that adds the greatest amount of volume. Now, knowing that the volume needed inside the tank is reduced by 2.98 %, and considering the 218 liters as the total volume, it is obtained that the PMD with automatic system represents an increase of 0.014486 % of the total volume of propellant, equivalent to 0.03 liters more inside the tank, this only having selected the automatic PMD.

So far it can be said that, although the physical parameters between the two options show a slight improvement for the use of the automatic system in the PMD, the real key parameter is the ability of each to localize the possible quantities of propellant dispersed inside the tank. For this, the ideal case will be to have a vane (semi-circle), with a radius equal to the working area described in chapter 2, this vane, although unfeasible, would represent what would be a 100 % sweep of the interior of the tank (with the automatic system). It would be assumed that after one turn it would have reached every part of the interior of the tank and thus there would be no accumulation of propellants without coming into contact with the PMD.

There are two cases, the first is the PMD device with the control system, which has the model vane 1 and 2, and also has a surface area in these vanes of 81272.575 mm^2 (value calculated based on the analysis of physical properties delivered by SolidWorks). The second case is a PMD device with acceleration limits, number of panels, etc., the same as case 1, with the difference that it does not have the control system, so instead of having both types of vane models, it has 4 vane model 1 around the sponge, so it has a surface area of 271251.42 mm^2, with a larger surface area than case 1, but with the difference that it remains static (it does not rotate).

Having the ideal case mentioned above, the PMD device with automatic control proposed in this project would cover 42.59606079 % of the tank's internal volume, on the other hand the PMD device without control system is only in contact with 0.09872 % of the tank's internal volume. Thus showing a great improvement and a greater ability to manage the propellant inside the fuel tank without the dependence on maneuvers in the satellite to ensure propellant extraction.

Chapter 4

Control system

For the development of the control system, a direct current motor was selected which will be the actuator of the system, for the implementation of the controller it is necessary to develop the linear modeling of the DC motor and obtain the differential equations, from which the transfer functions of each of the variables that have will be obtained. Once the above is finished, the state space representation will be obtained to finally make the simulation in Simulink.

4.1 Mathematical model:

The basic DC dynamo consists of an element with armature, brushes and field coils in series, parallel or a combination of them [5]. The most important elements of a DC motor are represented as follows:

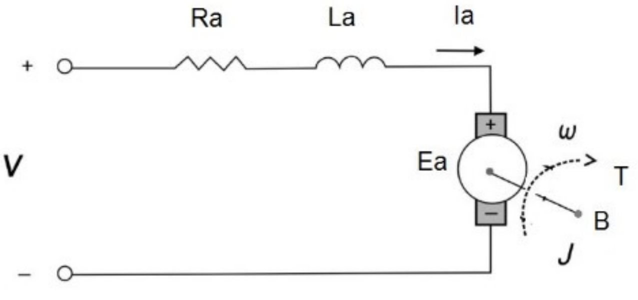


Figure 4.1: Electro-mechanical schematic of a direct current motor

From the circuit shown in Figure 4.1 the following differential equations are obtained which describe the behavior of the DC motor:

$$L\frac{di(t)}{dt} = v(t) - Ri(t) - E_a(t) \tag{4.1}$$

$$J\frac{dw(t)}{dt} = T_m(t) - Bw(t) \tag{4.2}$$

$$E_a(t) = K_a w(t) \tag{4.3}$$

$$T_m(t) = K_m i(t) \tag{4.4}$$

There is a set of equations that allow obtain a series of very useful transfer functions. Proceeding to by obtaining the Laplace transform of the above equations:

$$Lsi(s) = v(s) - Ri(s) - E_a(s) \tag{4.5}$$

$$Jsw(s) = T_m(s) - Bw(s) \tag{4.6}$$

$$E_a(s) = K_a w(s) \tag{4.7}$$

$$T_m(s) = K_m i(s) \tag{4.8}$$

At this point it is possible to obtain the transfer functions. Substituting equation 4.7 and equation 4.8 into equation 4.5 obtaining:

$$v(s) = \frac{(R + Ls)T_m(s)}{K_m} + K_a w(s) \tag{4.9}$$

The angular velocity can be obtained from equation 4.6:

$$w(s) = \frac{T_m(s)}{Js + B} \tag{4.10}$$

and substituting equation 4.10 in equation 4.9:

$$v(s) = \frac{(R + Ls)T_m(s)}{K_m} + K_a \frac{T_m(s)}{Js + B} \tag{4.11}$$

From here and from equation 4.8, the transfer function that relates the output (torque) and the input (voltage) of the system can be obtained:

$$v(s) = \frac{(R + Ls)(Js + B) + K_a K_m}{K_m(Js + B)} T_m(s) \tag{4.12}$$

Simplifying the transfer function:

$$\frac{T_m(s)}{v(s)} = \frac{K_m(Js + B)}{LJs^2 + (RJ + LB)s + RB + K_a K_m} \tag{4.13}$$

The direct current motor can be represented in block diagrams, where we can see that we will have an input such as voltage and this will give us several outputs such as current, angular speed and torque, and if a integration to the angular velocity will be able to obtain the position.

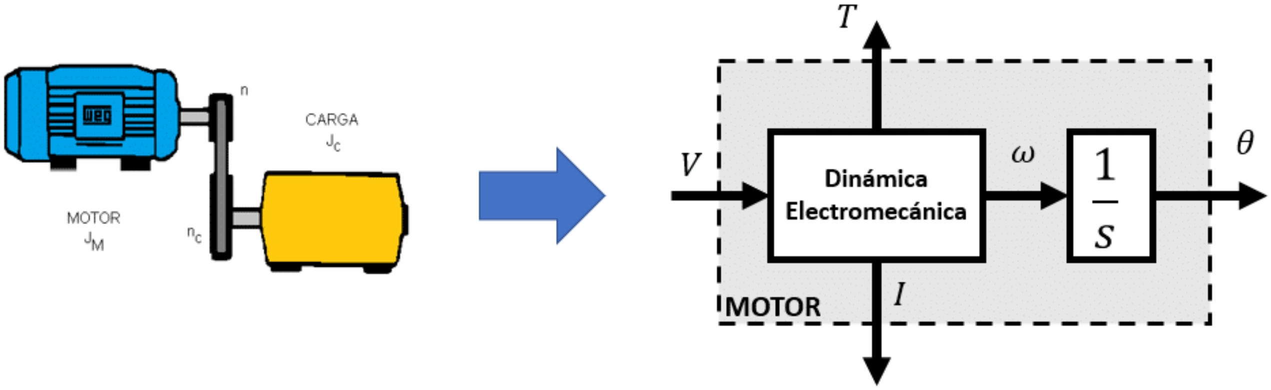


Figure 4.2: DC motor block diagram representation. [5]

As can be seen in figure 4.2, there are several outputs, so several transfer functions can be obtained, one for each output, resulting in: Transfer function (Counter electromotive force - voltage):

$$\frac{Ea(s)}{v(s)} = \frac{K_m K_a}{LJs^2 + (RJ + LB)s + RB + K_a K_m} \tag{4.14}$$

Transfer function (Armature Current - voltage):

$$\frac{i(s)}{v(s)} = \frac{Js + B}{LJs^2 + (RJ + LB)s + RB + K_a K_m} \tag{4.15}$$

Transfer function (Angular velocity - voltage):

$$\frac{w(s)}{v(s)} = \frac{K_m}{LJs^2 + (RJ + LB)s + RB + K_a K_m} \tag{4.16}$$

Transfer function (Position - voltage):

$$\frac{\theta(s)}{v(s)} = \frac{K_m}{s(LJs^2 + (RJ + LB)s + RB + K_a K_m)} \tag{4.17}$$

Now starting from the initial equations, 4.5, 4.6, 4.7, 4.8. The state space is constituted as follows. Define states

$$x_1 = w \qquad x_2 = i \qquad \dot{x_1} = \dot{w} \qquad \dot{x_2} = \dot{i} \tag{4.18}$$

Substitute into the differential equations

$$\dot{x_1} = -\frac{B}{J}x_1 + \frac{K_m}{J}x_2 \qquad \dot{x_2} = -\frac{R}{L}x_2 - \frac{K_a}{L}x_1 + \frac{1}{L}v \tag{4.19}$$

State space representation:

$$\begin{bmatrix} \dot{x_1} \\ \dot{x_2} \end{bmatrix} = \begin{bmatrix} -\frac{B}{J} & \frac{K_m}{J} \\ -\frac{K_a}{L} & -\frac{R}{L} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} 0 \\ \frac{1}{L} \end{bmatrix} v \tag{4.20}$$

$$\begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} \tag{4.21}$$

The output equation will depend on what we need to see, for example, in the 4.21 equation an identity matrix is placed where output 1 is the angular velocity and output 2 is the current. The system is governed by some constants such as moment of inertia, coefficient of friction, proportional constants Ka and Km, armature resistance and inductance. These variables are given by the DC motor that will be used in the system as well as the experimental analysis of the selected actuator.

Modeling the system and with the inconvenience of the lack of variables that must be obtained by experimentation, at this point only the implementation of a PD controller is proposed, because in the PD control the accuracy depends on the type of project, in any resolution, with strong inertia, this controller can do well.

Chapter 5

Conclusions

First of all, the different PMDs devices as well as their different types and combinations are reviewed. Its advantages and disadvantages were evaluated. Based on them, a decision to use a sponge in combination with a vane was made. Once the design procedure was established, calculations were done to evaluate the feasibility of the design as well as its performance. More details involving the sponge design were derived from the calculations such as the number of panels, the geometry, and the placement within the tank. Finally, with the dimensions specified we developed a CAD model in SolidWorks. The development and implementation of a control system in PMD devices is viable, as long as the conditions and objectives of the satellite to be used are carefully delimited, since a device of these characteristics presents several peculiarities, since at the same time being a mobile device (it rotates) will produce instability in the orientation of the satellite used, so in some satellites this will represent a great problem. In addition, implementing mobile parts inside the propellant tank implies an increase in the risks in the propulsion system.

Regarding the objectives set for this project, it was possible to reduce the volume of the PMD device inside by 2.98 %, which meant an increase of 0.014486 % of the propellant inside (0.03 liters). Therefore, although these percentages are relatively small, they have a direct positive impact on costs as well as an improvement in the efficiency of the system.

Secondly, obtaining a better extraction of the propellant, is perhaps the parameter that showed the most significant improvement, once the comparison between two equivalent PMD systems was made but with the difference of one counting the possibility of rotation, a sweep of 42 % was obtained. of the interior volume of the tank, a more than outstanding parameter compared to 0.098 % of the static PMD. These parameters are important for a pre-maneuver state of the satellite, once the ignition has started, both PMDs will present similar performances due to the acceleration that will occur in the satellite. On the other hand, this system used in spiner-type satellites may represent a viable option for cost reduction as well as for obtaining better performance in propellant extraction.

The main utility of this project is the implementation of the device in satellites that contain a unified propulsion system, such as meteosat second generation (MSG). Since having several propellant tanks, when more extraction occurs in one of the tanks, the weight distribution in the satellite changes, which generates instability. This device will help to have a more equitable extraction in each one and thus maintain the mass distribution in the satellite.

There are still some relevant analyses that are yet to be done in order to correctly evaluate the performance of the full integrated system. Those are noted below.

- Do the complete analysis of the vane that is used to refill the sponge (acceleration limit, upper and lower radius, and flow rate). Through this analysis, one should validate the viability of the vane, as well as some other factors such as the time it takes for the vane to refill the sponge. Hence, the required delay between firing of the thruster. It should be underlined that the acceleration expected during the vane acting period is really low, thus, there should not be any concern regarding the viability of the vane, rather the focus should be on the performance.
- Selection and implementation of a humidity sensor for greater precision.
- Develop an experimental set up to carry out a test in microgravity, and analyze the performance of the device as well as the interaction with surface tension and adverse acceleration.
- Determine how the system is anchored to the tank. The sponge and vanes are connected components that should be elevated from the tank bottom in order to allow free flow of propellant, despite the height separation needing to be low in order to create enough surface tension force between the propellant in the PMD and the tank. The reasonable approach would be to somehow attach the sponge to the bottom of the tank, where the attachment should be as least intrusive as possible, the smallest, and as near to the outlet as possible. The anchor point represents not only a blocking path for the propellant but also a leaking path, thus the ideal position would be as near to the outlet as possible while holding the sponge, this way the propellant will not leak, as it would be already in contact with the bottom at that part.
- Determine the constants of the mathematical model of the actuator, to later propose a suitable PD controller for the system.

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