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SIMULATION OF A LIQUID ROCKET ENGINE

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Abstract

A study has been carried out of the dynamic behaviour of the liquid propellant that circulates through the different engine components of a liquid.fuelled rocket. As a model we used the Vulcain engine, the main engine of the European Ariane rocket, which is fuelled by liquid hydrogen and oxygen. For this purpose, a library has been created in EcosimPro which includes the rocket components, as well as auxiliary functions to calculate the physical properties of the substances (both reagent and product) which take part in the propulsion process (combustion).

Key words: Simulation, rocket, dynamic fluid, liquid fuel, instability, combustion.

1 INTRODUCTION

Certain tests are necessary before starting up a space vehicle and carrying them out on ready built equipment involves high costs and a great deal of risk for the manufacturer, which is why an alternative solution to the real tests has been sought. This alternative consists in verifying the correct operation of the rocket by computerised simulation.

A simulation tool has therefore been created which is designed for use with any type of chemical rocket based on a gas generator cycle which uses hydrogen and oxygen as liquid fuels. However, if we have the relevant data on their physical properties, this specification can be extended to other substances [7].

To compare the data obtained with the program we used a model of the European Ariane 5 rocket which uses the Vulcain propulsion engine and two solid fuel booster rockets for the launch, which in this case are only contemplated as thrust and substance input to the mathematical model.

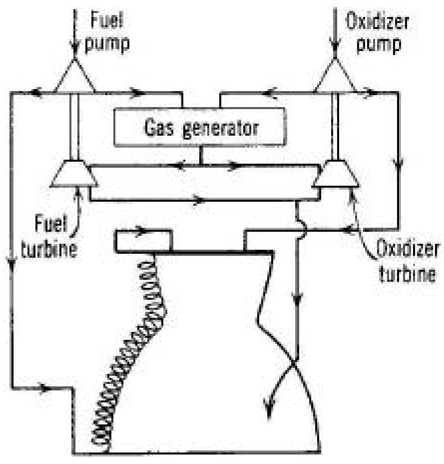

Figure 1: Sketch of a Vulcain type engine [6]

The following are some of the modifications made with respect to the original sketch of the Ariane rocket:

- The use of a single turbine to supply power to the two centrifugal pumps for the respective propellant fluids.

- The addition of a shaft for each pump, which means that the speed of rotation must be reduced with the use of gears; in this case for the oxygen pump which rotates at a lower speed.

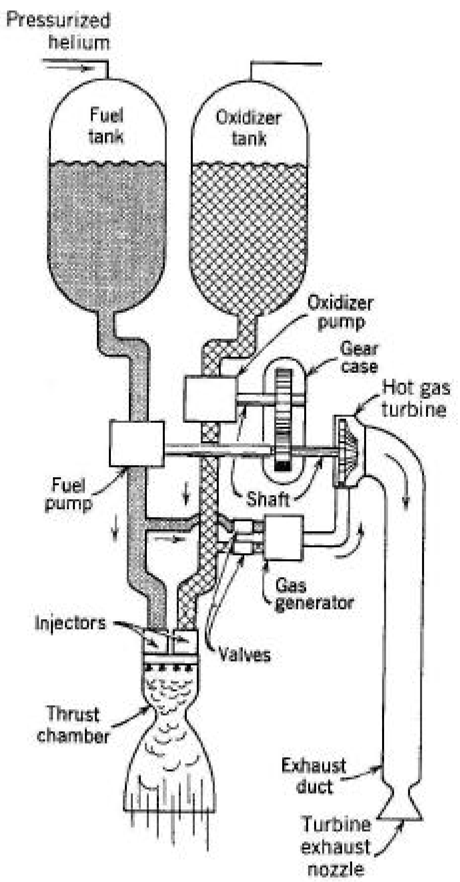

Figure 2: Sketch of the rocket implemented

One of the advantages gained by using the EcosimPro program is that, once the basic components are available, the number of components and the connections between them can be easily modified.

The basic components in this case are:

- Fuel storage tank
- Connection pipe between components
- Centrifugal pump
- Gas generator or precombustor
- Turbine
- Injectors
- Combustion chamber
- Heat exchanger
- Nozzle

The equations and the characteristics which define each of the above components will be specified later on.

2 MATHEMATICAL MODEL OF THE DYNAMIC EQUATIONS

Consideration has been given to four different types of dynamic equations:

- Equations that express the inertia of the liquid caused by pressure fluctuations.
- Equations that express the fluid storage capacity of components due to certain compressibility of the liquid.
- Equations that express the shaft rotation inertia in the turbine pumps.
- Equations that express the time-lag in the combustion chamber.

2.1 INERTIA OF THE FLUID WITH VARIATIONS IN PRESSURE

Based on Newton’s second law, in a horizontal feed line with a length *L* and constant section *A*, through which flows a liquid with a density ρ at a speed ν, considering the loss of pressure due to friction forces and applying the continuity equation $\dot{m} = rvA$, the following deduction can be made:

$$F = ma = \left(\frac{L}{A}\right)\frac{d\dot{m}}{dt} = P_{in} - P_{out} - f_D \frac{L}{D}\frac{\dot{m}^2}{2rA^2} \quad (1)$$

Where:

F is the net force which the line withstands,
P_{in} is the line inlet pressure,
P_{out} is the line output pressure,
$\dot{m}$ is the mass flow that circulates through the line,
D is the diameter of section A,
f_D is the friction factor, which is calculated using a Moody graph correlation.

Equation 1 is applied to the tanks, the different pipelines and the heat exchanger.

It should, however, be pointed out that these elements have been considered as vertical lines, which is why we have added a height variation term *h* to equation 1 which is expressed as , where g is the acceleration of gravity.

2.2 CAPACITY OF THE FLUID WITH VARIATIONS IN PRESSURE

Working with the same case, in a line which receives a fluid flow $\dot{m}_{in}$ and which discharges another flow $\dot{m}_{out}$, considering that said flow has a certain compressibility $k = dr / rdP$ at a constant volume AL, it can be deduced that:

$$\dot{m}_{in} - \dot{m}_{out} = \frac{dm}{dt} = \frac{d(rAL)}{dt} = k(rAL)\frac{dP}{dt} \quad (2)$$

Equation 2 is applied to the pipes, the gas generator, the injectors and the heat exchanger.

2.3 ROTATIONAL INERTIA ON THE SHAFT

In the case of a turbopump whose rotor has an inertia I, and whose shaft rotates at an angular velocity Ω, the following dynamic equation is applied:

$$\Omega \frac{d\Omega}{dt} = \frac{P_t - P_p}{I} \qquad (3)$$

Where:

P_t is the power supplied by the turbine,

P_p is the power used by the pump.

On this basis, the inertia has been included on both shafts in module I.

2.4 TIME-LAG IN THE COMBUSTION CHAMBER

One of the possible causes of problems in the correct operation of the rocket is the existence of instabilities in the combustion chamber. There are different types of instabilities, but in this case we have only dealt with chugging which occurs at low frequencies and is analytically predictable [2].

Considering the complexity of the whole combustion process, a certain length of time is required to convert fuel from the moment of injection until the products of the composition reach a state of equilibrium. This time-lag τ_c is determined not only by means of the chemical kinetics of the reaction, but also considering the atomisation time after the liquid is injected, as well as the mix of reagents.

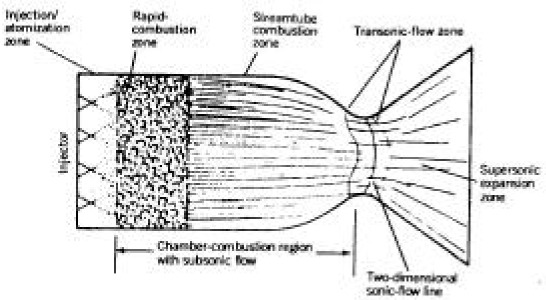

Figure 3: Sketch of the processes in the combustion chamber [6]

The balance of mass in a combustion chamber with a volume V_{cc} at a pressure P_c and temperature T_c can be expressed with the following equation:

$$\frac{d}{dt}\left(\frac{P_C V_{CC}}{R^* T_C}\right) = \dot{m}_{ox}\left(t - t_c\right) + \dot{m}_f\left(t - t_c\right) - \dot{m}_{out} \qquad (4)$$

Where:

R^* represents the constant of the ideal gases for the molecular mass mix M,

$\dot{m}_{ox}\left(t - t_c\right)$ is the flow of oxidiser injected within a time $\left(t - t_c\right)$,

$\dot{m}_f\left(t - t_c\right)$ is the flow of reducing agent injected within a time $\left(t - t_c\right)$,

$\dot{m}_{out} = \frac{P_c A_t}{c^*}$ is the flow of products from the chamber within a time *t*.

Finally, the characteristic velocity c^* is defined on the basis of the thermodynamic properties of the isentropic flow with specific heat rates γ:

$$c^* = \frac{\sqrt{g R^* T_C}}{g\sqrt{\left(2/g + 1\right)^{\frac{g+1}{g-1}}}}$$

On the other hand, we know that τ_r, is the residence time or the time that the gases remain in the combustion chamber. Based on the characteristics of the combustion chamber, this can be calculated as the characteristic length $L^* = V_{CC}/A_t$ [1] which, in turn, is a function of the volume of the chamber and of the area of the neck A_t:

$$t_r = \frac{L^*}{g c^*}\left(\frac{g+1}{2}\right)^{\frac{g+1}{g-1}}$$

3 COMPONENTS

3.1 STORAGE TANKS

The fuel used for the model rocket is comprised of oxidiser: liquid oxygen, and reducing agent: liquid hydrogen; they are both cryogenic substances. Because of this, the tank storage temperature is 90 K and 20 K, respectively.

In addition, it is recommended that these tanks be slightly pressurised (4 atm) so as to prevent possible cavitation in the pumps that drive the gases to the combustion chamber; but never to excess, because this would mean having to reinforce the walls of the tanks which would result in an excessive increase in the weight of the rocket.

The dynamic equation that governs this component is that defined in section 2.1.

3.2 Connecting Pipes

Two types of pipes have been designed for the model. On the one hand, those that connect the storage tanks with the pumps are considered to be vertical lines and, on the other hand, those that connect the pump outlet with the elements located ahead of them are considered to be horizontal lines.

Equations 1 and 2 are used for their dynamic characterisation.

3.3 CENTRIFUGAL PUMPS

Two centrifugal pumps have been designed to drive the liquid oxygen and hydrogen [4].

Although the only dynamic equation contemplated by these pumps is that which corresponds to their rotational inertia (equation 3), it was necessary to define an auxiliary second-level equation to try to simulate the actuation map for each pump [5], relating the flow coefficient ϕ with the pressure coefficient ψ.

$$f = f\left(\frac{\dot{m}}{r\Omega}\right) \quad \text{y} \quad y = f\left(\frac{\Delta P}{r\Omega^2}\right)$$

In addition, we have a correlation between the pump efficiency η and the same coefficient ϕ [5].

It is important to point out that no consideration is given to the possibility of cavitation for the pumps, assuming that they have already been designed in order to prevent such a phenomenon.

3.4 GAS GENERATOR

Also known as a precombustor, its mission is to generate a hot gas current at high pressure through the combustion of a small proportion taken from the main flow.

It has been simplified as a longitudinal enclosure, similar to a pipe, where combustion reaction takes place at a determined pressure and temperature. In this case, the working conditions are 90 atm and 980 K.

The only dynamic equation present is that which considers the fluid capacity with variations in pressure. However, a more detailed study could take into consideration the possibility of instabilities in the same gas generator.

3.5 TURBINE

The gas generated in the precombustor is driven to the turbine, where its energy is used to turn the turbine blades. The rotational speed of the shaft produces the power required by the pumps.

The design is based on that of an isentropic turbine, with choked gas at exit (maximum speed is sonic) and with a pressure ratio equal to 2.

3.6 HEAT EXCHANGER

It is absolutely essential to introduce a heat exchanger which cools the gas outlet wall after the combustion chamber. Temperatures of up to 3500 K can be reached in the throat, which would be capable of melting down any metal used in its construction.

The heat emitted by these gases is directly proportional to the product of the gas film coefficient h_g in the nozzle (which is calculated with Bartz's equation) and the difference between the temperature of the chamber and the adiabatic temperature of the wall.

To absorb the heat emitted, the actual liquid hydrogen from the turbopump is used as the cooling fluid and it is subsequently sent to the combustion chamber injectors.

This component has been modelled as though it were a pipe with a semicircular section, using dynamic equations 1 and 2 which were referred to earlier.

3.7 INJECTORS

The injectors are characterised by their pressure drop, calculated on the basis of the flow of fluid circulating through them, of the orifice area, and of the flow coefficient C_d corresponding to the design selected for each of the reagents.

Dynamic equation 2 is applied to the volume of the distributor which precedes the injectors.

3.8 COMBUSTION CHAMBER

The equations necessary to build a model of the combustion chamber have already been addressed in section 2.4.

The physical dimensions of the chamber, as well as of the remaining components specified, could be introduced by the user, whereas the thermo-chemical data are calculated internally based on the relationship between fuel flows at the chamber inlet.

3.9 NOZZLE

The objective of the nozzle equations is to calculate the thrust produced by the engine as it expels a determined flow of gases at a certain speed, pressure and temperature.

Also included are the equations to calculate the heat exchanged with the cooling system. To facilitate the development of the integral on the transmission surface, a cone-shape nozzle is considered.

Thanks to the thrust which is also generated by the solid rocket boosters, rocket lift-off follows a vertical trajectory which is, in turn, calculated in another component created specially for the purpose.

4 RESULTS

As soon as we begin to effectively connect all the components implemented in EcosimPro, an overall component will be generated which simulates the rocket and for which appropriate experiments are carried out.

The user can modify the physical dimensions and other characteristics of the design of each of the elements with the use of Smart Sketch. By default, these specifications correspond to known data for the Ariane rocket and its Vulcain engine (see attachment).

Simulation begins in a situation whereby the engine is already operating normally; in other words, the lines are full of circulating fluid, the pump and turbine shafts are rotating at design speed, and combustion in the chamber is already effective.

Initial values must be specified for the dynamic variables, these being: the initial mass in the tanks (expressed as liquid level), the emptying flow of the tanks, the load flow of the injectors, and the pressure in the lines, the gas generator and the gas heat exchanger.

It is also necessary to establish some initial values to serve as guidance for some of the algebraic variables of the system, in order to facilitate the mathematical resolution of the problem.

Physically, the only degree of freedom that exists is the flow of gas that circulates through the turbine which, in turn, is the variable that controls the power generated by the turbine.

All these initial values which are necessary for the simulation are also based on the technical specifications of the Vulcain engine.

When we run the experiment we can see a certain oscillation in the dynamic variables, which lasts about 5 seconds, before reaching the stationary state. If we leave the experiment operating in this state, we can see that rocket lift-off is normal.

In addition, the response of the system was verified when, during execution, a disturbance was introduced in the combustion chamber, causing an increase of 5% in the pressure value in the chamber. In this situation, if the system is stable, the disturbance can be seen to be mitigated. If, on the other hand, the selected engine design has repercussions on an unstable system, the disturbance will increase.

It is important to point out that the selected integration time has to be less than any of the characteristic times of the respective dynamic equations used; otherwise, some of the processes may never take place.

A comparison of the results obtained by means of simulation in EcosimPro with the data known for the Vulcain case verifies that the mathematical model corresponds to reality with an error of no more than 5%. For example, the value obtained for the combustion chamber pressure is 113 atm, compared to the 110 atm working pressure of the Vulcain engine; the rotating speeds of the hydrogen and oxygen pump shafts are 3430 rad/s and 1375 rad/s respectively, whereas the specifications of the Vulcain engine indicate values of 3500 rad/s and 1400 rad/s.

5 CONCLUSIONS

The simulation of a liquid rocket engine with the use of EcosimPro proves that it is a useful, reliable tool for carrying out experiments both of stationary state operation and of the dynamic processes that take place in its core, such as, for example, system behaviour in the light of possible instabilities in the combustion chamber. It could also be useful for generating flow controllers or dynamic stabilisers.

Attachment

ARIANE
Total height = 30.5 m
Average diameter = 5 m
Structural mass = 170000 kg
Thrust = 11360 kN (including solid rocket booster)
Oxygen tank capacity = 130000 kg
Hydrogen tank capacity = 25000 kg
Actuation time = 570 s

SOLID ROCKET BOOSTERS (2)
Height = 30 m
Diameter = 3 m
Structural mass = 230000 kg

Thrust = 6360 kN
Specific impetus = 275 s
Actuation time = 125 s
Spent fuel flow = 2350 kg/s

VULCAIN
Engine height = 3 m
Structural mass = 1700 kg
Thrust = 1140 kN
Specific impetus = 421 s
Effective emission speed (c) = 4000 m/s (maximum that can be reached in the atmosphere)

Temperature in the oxygen tank = 90 K
Temperature in the hydrogen tank = 20 K

Combustion chamber temperature = 3500 K
Combustion chamber pressure = 11.0 MPa

Temperature in the gas generator = 9.0 MPa
Pressure in the gas generator = 1050 K
Temperature in the turbine = 900 K

Flow of propellant fluid = 271 kg/s
Flow in the gas generator = 8.8 kg/s
Flow in the combustion chamber = 262 kg/s

Ratio of overall flow mix = 5.3
Ratio in the gas generator = 0.9
Ratio in the combustion chamber = 6.3

Oxygen turbopump:
Power = 3700 kW
Speed of rotation = 1400 rad/s (13400 rpm)
Inlet/outlet pressure = 0.35 MPa/12.5 MPa

Hydrogen turbopump:
Power = 11900 kW
Speed of rotation = 3500 rad/s (33200 rpm)
Inlet/outlet pressure = 0.3 MPa/16.0 MPa

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