# ARIANE 5 LAUNCHER - FINITE ELEMENT MODELING OF A VULCAIN 1 ENGINE

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## Introduction

Following the failure of Ariane 5 ECA maiden flight 157 in December 2002 (mounting a Vulcain 2 engine and an ESC-A cryogenic upper stage), a Recovery Plan was set up at European level in order to ensure the fastest and safest Return to Flight. The main target defined at the time was to make sure of launch service continuity thanks to Ariane 5 Generic launchers (Vulcain1 engine and EPS storable fuel upper stage), waiting to prepare again for an ECA launch.

The Recovery Plan was directed by a task force including management staff from ESA, CNES, Arianespace and the industrial partners. The plans of action introduced as a result of this work led to the introduction of independent cross-check procedures where tight margins or doubts concerning the representativity of models or tests exist.

In this context, GECI technologies has been working many months under a CNES contract to develop a finite element model of the VULCAIN 1 main cryogenic stage engine. The aim of this work has been to build a powerful tool, allowing CNES to carry out an independent cross-check of the parallel industrial activities.

As to satisfy this request, the Vulcain 1 engine model had to represent as close as possible the real dynamic behavior of the engine, being at the same time easy to handle and to modify. It had notably to allow the recovery of the interaction efforts between the different engine components. The software used for modeling and mesh definition were Ideas version 8 and 10 and Ansa version 11.3.2, while Nastran (version 2001) was used as a solver.

At the end of the activity, GECI supplied CNES with a sound model of the Vulcain 1 engine, counting about 93000 elements and 197500 nodes. CNES possesses therefore today a tool allowing them to make independent simulation of the engine dynamic behavior.

The Vulcain1 engine is one of the main components propelling the launcher aft body. Functioning initially in parallel to the two EAP solid boosters ("Etage d'Accélération à Poudre"), it allows the lift off of the launcher, and the propulsion of the main cryogenic stage till 450 seconds. The management of the ARIANE 5 development program was ensured by CNES, on behalf of the European Space Agency. The Vulcain 1 engine development was lead by SNECMA, European leader in space propulsion.

The engine itself is constituted by four main sub-systems: the thrust chamber, two turbo pumps and the gas generator. The thrust chamber consists essentially of the combustion chamber, of a nozzle, and a dome. The engine is connected to the main launcher stage by a gimbals joint, two servo-jacks (which pilot the engine), and two feed lines.

This paper will describe the work performed at GECI France in order to build up and validate the Vulcain 1 engine model. At first, the engine structure was analysed, considering material and drawings of the main elements. The kinematics connection between all these elements was attentively evaluated. After, all elements were fitted together taking into account the engine kinematics. Some tests were applied onto the model to check its correct behaviour and the mesh validity.

The global model of the engine was finally calibrated on available experimental data, in order to be representative of the real engine dynamic behaviour. A collection of modes was selected for this purpose, and a comparison of frequencies and modes shape between experimental and finite element results allowed the model validation. When a delta was observed, the model was refined considering a more detailed geometry, a more realistic connection modelling, or some other wedge methodologies. A discrepancy up to 5% has been achieved for modes below 40 Hz, and up to 10% for higher ones (modes up to 100 Hz have been considered).

## Finite element modeling of a Vulcain 1

Using Ideas, the geometry of a majority of components was slightly redrawn with some geometrical simplifications, without a significant impact on the quality of the model. The components selected for modeling are those with a remarkable behavior in the range of 0 to 100 Hz, as the propulsion chamber, turbo pumps, the gas generator, the thermal protection, lines, valves and supports. Each component is meshed by using element type suitable to their definition and behavior.

Once the components independently modeled, they are fitted together, under the software ANSA, taking into account the engine kinematics. The different components connections are made either by continuity of meshing (clamped junction), or using rigid elements, whose degrees of freedom are correctly free to insure the wished kinematics behavior of the junction.

During the modeling, the validity and the quality of the meshing were regularly verified, to ensure the correct development of the project. Free/free modal analyses were realized on each singular component at a time, and on the complete engine at the end, to verify their correct rigid body behavior.

Hereafter, the basic modeling approach for the main engine components is detailed.

### *Dome and injection plate*

The dome and the injection plate are massive metal parts, which don’t need a fine modeling in the case of a dynamic calculation. However, they occupy a considerable volume and are joining other engine components. They have therefore been modeled by a representative geometry, and meshed using 3D elements. Only the injectors were considered as a distributed mass on the lower surface of the injection plate.

*The combustion chamber*

A specific attention was devoted to the modeling of the combustion chamber (fig. 1), which is a complex and essential component of the engine. For this part, different methodologies of modeling have been used.

The cooling of the chamber is realized by several channels. The chamber internal skin thickness varies gradually along the engine main axis direction. Because of such a complexity, a simplification is imperative.

To limit the final number of degrees of freedom, five times less channels were considered for modeling, and a factor five was applied on the channels wall thickness to compensate this simplification.

Other simplifications were at the interface points with actuators and other engine elements, where the connecting flange were modeled using 2D elements.

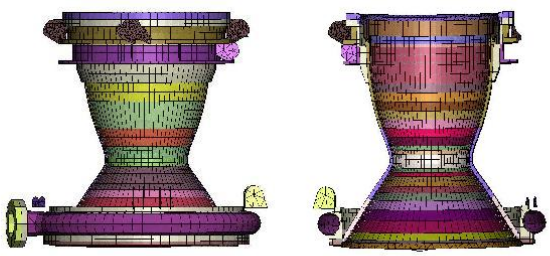

Fig. 1

*Nozzle*

The modeling of the nozzle (fig. 2) follows the same logic of the combustion chamber modeling. Notably concerning the modeling of cooling channels, the internal and external skins (consideration of ¼ of total channels).

The main difference between the nozzle and the combustion chamber configuration is the constant thickness of the internal skin, and the fact that some stiffeners are mounted on the external skin of the nozzle, to increase its stiffness.

Fig. 2

*Turbo pumps*

The turbo pumps being important elements, highly impacting the dynamic behavior of the engine itself, a big attention was devoted to the modeling of main internal and external turbo pumps elements.

Adjusting the mass of each sub-assembly to be as representative as possible of the real components definition has been essential to the turbo pumps calibration.

*The engine thermal protection (PTM)*

The engine thermal protection (fig. 3) is constituted by both metallic parts and composite materials. It has been modeled by 2D elements with suitable physical and material properties.

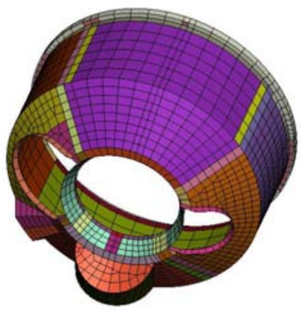

Fig. 3

*The external interfaces*

The components, which insure the connection between the Vulcain 1 engine and the upper part of the stage / launcher, are the gimbals joint and the servo-jacks.

The gimbals joint is a very massive and stiff element. The stiffness of its upper and lower parts is known. A simple modeling via rigid elements, springs and punctual masses allows therefore obtaining a good representation of the component, without increasing the complexity of the modeling.

As the gimbals joint, servo-jacks insure the transfer of the engine efforts to the launcher. Moreover, they also allow to pilot the engine thrust in the desired direction. The modeling methodology is identical.

### *Others*

Other components such as gas generator, lines, valves and supports have been modeled in agreement with their own geometry. In case of very stiff components, the geometrical characteristic have been simplified using rigid elements and punctual masses.

Various techniques were used in order to have an engine dynamic behavior the most representative as possible of the real engine behavior. For example, for the modeling of the lines ball joints several rigid elements were used, while their degrees of freedom were defined accordingly. This modeling makes it possible to tune the stiffness of the different connections between all engine components.

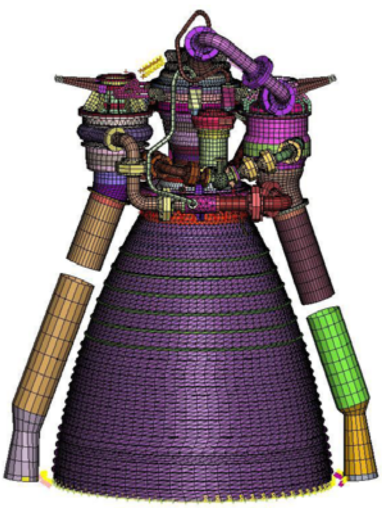

Fig. 4

## Validation of the VULCAIN 1 ENGINE

Once the mesh was defined and checked, the global model (fig. 4) of the engine was compared and tuned with available experimental data in order to be representative of the real engine behavior. The results of MQD ("Maquette de Qualification Dynamique") tests were used for this purpose.

Set-up conditions of the engine during test are known. They have been reproduced in the modeling, allowing to calibrate the engine in identical conditions to those of the experimental tests.

The work of calibration was based on the comparison between experimental and finite element frequencies and modes shape. A collection of representative modes was selected to be able to cover the whole engine dynamic behavior.

### *MQD Set-up conditions*

To perform the test, special boundary conditions were required. The engine was at ambient temperature, without any pressure or temperature fields applied (passive status).

The engine is connected to the test bench via an adapter. The adapter itself is attached onto the seismic basement through a steel plate. This system has been taken into account in the model using rigid elements, clamped.

During test the LCO ("Ligne de Chambre Oxygène") line is full of water, while other lines are pressurized with gas. This pressure has been considered in the model. The mass induced by the water is also taken into account, and the stiffness induced by the pressure is considered in the calculation.

The PTM is removed to facilitate access and inspection of the engine.

Servo-jacks allow to pilot the engine during flight, they insure an important interface with the rest of the launcher. Dummies were used during tests to insure the transmission of the efforts and the stability of the test set-up. They also impact the engine dynamic behavior.

The dummy stiffness, which is known, was therefore integrated into the model.

The gimbals joint was blocked, to stiff the engine.

### *Calibration methodologies*

In order to obtain a Vulcain 1 engine models as close as possible to the real engine dynamic behavior, we chose to concentrate on two main objectives:

- Calibration of mass components and of total engine mass.
- Calibration of modal behavior of single components (whenever experimental results available, as for the PTM and the nozzle e.g.), and of engine main modes.

To perform the mass calibration, we tried to find a good compromise between a detailed geometry representation, and a reasonable complexity of the models. For this reason, a few small elements have not been modeled. They represent less than 10% of the total mass. It was verified that this delta does not impact the quality of the model, and the engine dynamic behavior.

The final comparison between model and test results was performed on both mass and inertia criteria.

The thrust chamber being the largest part of the engine, a mass comparison on this component has been performed with the highest accuracy. A discrepancy of 0.5 % was found. This delta was considered low enough not to impact the engine dynamic behavior. The inertia found are almost the same ones in the three directions, what shows the perfect symmetry of the thrust chamber model. They are between 3 and 4 % of the real values. Important simplifications having been operated with respect to the actual chamber geometry, this result remains very satisfactory.

To assure the best possible similarity between the modes obtained experimentally and the modes obtained by finite element model, different components have been calibrated in different ways.

The parameters allowing a good calibration of the assembly modes (fig. 5) depend on the external interfaces. The feed line stiffness is negligible by comparison with the other components, and they are not taken into account. Only the stiffness of the other external interfaces have therefore been considered, which allow obtaining correctly the assembly modes.

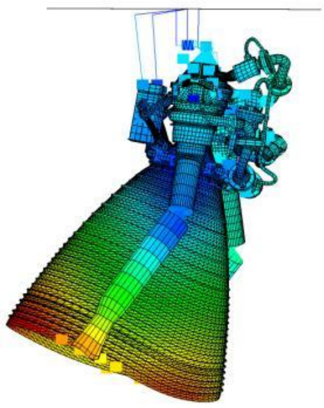

Fig. 5

The nozzle designer, VOLVO in Sweden, provides a modal base of the nozzle  clamped at the level of its flange (obtained by means of a FEM). This result has been used for a comparison with our model, considered with analogous boundary conditions. The conclusion are pretty good, and show that the nozzle does not need any specific adaptation

The kinematics of the lower attachments, between nozzle and exhaust lines, results therefore to be the only parameter which can influence the ovalization modes (fig. 6), once the nozzle is inserted in the global engine model.

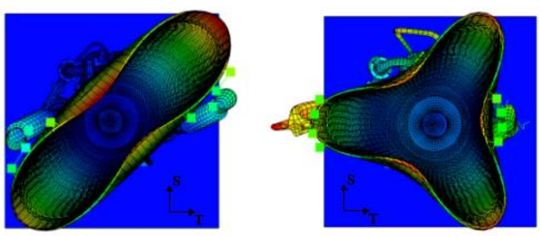

Fig. 6

The mass of the turbo pump was accurately tuned during modeling, in order for each Turbo pump part to be as representative as possible of the real mass. The turbo pumps themselves being pretty stiff, only the kinematics of their support can therefore be responsible of their modal behavior, once integrated in the engine global model (Fig. 7)

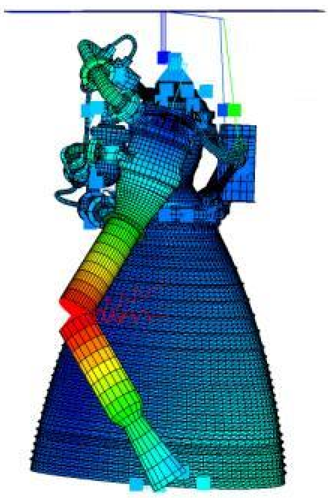

Fig. 7

The modeling of the chamber and turbine lines has been performed taking into account all elements, which are responsible for the line kinematics behavior. Spring elements have been fixed at the boundary. These springs can then be used as parameters, to allow lines calibration.

To obtain the PTM ovalization modes, the modeling and the stiffness of the metallic frame is as detailed as possible. Concerning the PTM longitudinal modes, the tuning is performed playing on the mechanical characteristic of the composite material.

To tune the modal base of the engine global model onto the test results, several runs were necessary. An iterative process was performed, consisting in modifying one by one the parameters every run, up to when a satisfactory compliance with the experimental data was found.

The calibration was made in two phases:

- Calibration of engine alone, without PTM
- Calibration of the Engine Thermal Protection (PTM) alone

The final global modal base is then obtained running a modal analysis of the engine + PTM model. It shows the coupling between engine modes and PTM modes.

*Engine modal base*

The following results are the comparison between modes obtained experimentally and modes obtained by the finite element model. The delta is calculated between MQD and FEM frequencies.

Table 1

| **Mode description** | **Delta between MQD and MEF Frequencies** |
|---|---|
| Pendulum 1 | +1,2 % |
| Pendulum 2 | +0,3 % |
| Torsion | +2,5 % |
| 2 lobes divergent | +5,4 % |
| 2 lobes divergent | +0,4 % |
| Chamber flexion 1 | +13,3 % |
| Chamber flexion 2 | +4,0 % |
| TPO mode 1 | +2,4 % |
| TPO mode 2 | +3,9 % |
| GG | +4,8 % |
| Line mode | +1,0 % |
| TPH mode | +0,9 % |
| 3 lobes divergent | +3,6 % |

Note: Some modes are not pure, but they consist of modes coupling of a few major components.

The two chamber bending modes have been the hardest modes to be tuned. Several parameters can in fact influence these modes, and they make it difficult to reproduce their exact frequency. In the end, after several calculations, the sensitive parameter was nevertheless identified to be the servo-jacks stiffness.

As the servo-jacks used during experimental tests are dummy servo-jacks, the final calibration of the bending modes was not identified as a priority. This modes are in fact much better tuned when the comparison with flight experimental data is performed, and they were demonstrated to not particularly influence other modes. The good quality of the model was therefore confirmed after the comparison.

### *PTM Modal base*

PTM modal tests have been performed on a thermal protection mounted on the engine. To tune the finite element model, we considered at first the PTM alone, with boundary conditions representative of the engine interfaces. This approach allowed to easy the calculation and reduce the runs' time. Afterwards, the PTM was integrated to the engine, in order to be fully representative of the test conditions.

Here follow the results:

Table 2

| | **Delta between MQD and MEF Frequencies** | |
|---|---|---|
| **Mode description** | **PTM alone** | **PTM on engine** |
| 1 lobe | +0,4 % | +2,0 % |
| 1 lobe | +8,3 % | +0,1 % |
| 3 lobes | +5,2 % | +4,1 % |
| Longitudinal | +7,3 % | +8,1 % |
| 4 lobes | +1,9 % | +3,0 % |
| 4 lobes | +6,8 % | +5,9 % |

The PTM is a component difficult to tune, because the driving parameters for the calibration are the material properties. It is in fact essentially constituted of composite materials, held together via metallic frames and stiffeners. The main modes of the PTM were therefore tuned mainly playing with the following parameters:

- Physical properties of the composite material
- Definition and characteristic of the metallic parts
- Boundary conditions (supports / attachments stiffness)

At the end, a satisfactory modal base was found. Once the PTM is fixed to the engine, deltas of frequency are in fact low enough to guarantee a good quality of the model.

### *Engine+ PTM modal base*

At the end engine and PTM models, tuned and validated, were assembled together. A global modal analysis was then run to identify the total engine behavior. All engine and PTM main modes, the ones already identified and new coupled ones, were identified.

## Conclusion

The main objective of this document was to explain the way to calibrate a complete engine model, and in this particular case how the tuning was achieved on the Vulcain 1 engine finite elements model. This work allowed the French Space Agency, CNES, to obtain a powerful tool, with which it was possible to achieve suitable results for cross check purposes.

Because of the high realistic behavior of the model, other exploitations could be possible in the future, as for example the condensation of the model in order to insert it in a global launcher model, for further studies. Furthermore, its modularity would allow to easily adapt it in case of any modification to come.

## References

[1] Definition files and documents of definition CNES
[2] Test documents IABG.