CARMEN, liquid propulsion systems simulation platform

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CNES Launchers Directorate (DLA) has to maintain a high level of expertise in order to achieve its missions regarding the exploitation of the Ariane 5 family launchers and to prepare the future of launchers. For that purpose, developing and using numerical simulation tools is of key importance.

CARMEN software is CNES reference tool for propulsion systems simulation, from their design to their exploitation.

CARMEN regroups several CNES software, among them CARDIM, for engines thermodynamics and geometric design, and CARSTAT/CARINS, for analyzing functional behavior of propulsion systems in stationary (CARSTAT) or transient modes (CARINS).

This paper will extensively present CARMEN software development status and capabilities.

1. INTRODUCTION

CNES Launchers Directorate (DLA) has to maintain a high level of expertise in order to achieve its missions regarding the exploitation of the ARIANE 5 family launchers and to prepare the future of launchers. For that purpose, developing and using numerical simulation tools is of key importance. Furthermore, having a software that allows to capitalize the know-how and technical skills of different specialties encountered in propulsion is a strong asset for CNES.

CARMEN is DLA software platform that regroups all the necessary tools for engine system design and analysis. As can be seen in figure 1, CARMEN is divided in two modules: CARDIM and CARFONC. CARDIM allows the calculation of engine thermodynamic cycle (CARMOT) and the preliminary geometric design of the subsystems (CARSYS). CARFONC allows steady state operation (CARSTAT) and transients prediction and analysis(CARINS).

All these sub-modules are designed to be able to communicate easily with each other: they have a common graphic user interface in JAVA and they are able to exchange and use each others relevant results files.

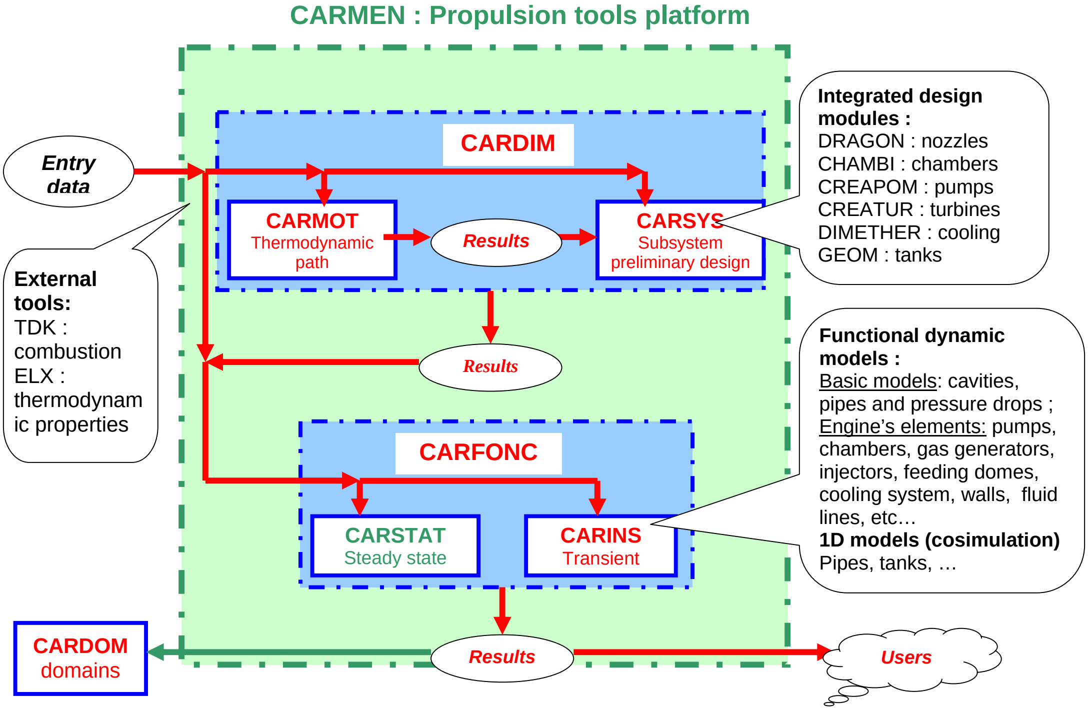

Figure 1 –CARMEN software platform

CARMOT, CARSTAT and CARINS are based on symbolic formulas manipulation with a computer algebra system named MAXIMA which is open source. This method allows to split the simulation in three steps, as shown in figure 2:

- Modeling through a graphic user interface, which consists in choosing components and associated models in a library and connecting them
- Automatic generation of a dedicated and optimized executable simulator linked with a solver: this is achieved through the sorting out of the equations by MAXIMA, the creation and compilation of a FORTRAN code and the link with the solver which differs between CARDIM and CARFONC
- Simulation and exploitation of the results through the graphic user interface.
- After achieving those steps, the user has access to several features depending on the module such as parametric studies, sensitivity analyses, etc…

What makes CARMEN so special is also the possibility that is given to the user to implement his own physical models directly through the graphic user interface. The user does not need to know how to code, since the equations can be written literally through a dedicated tool of the interface and associated with an engine element in a customized library. If he prefers, the user can also write his own models using several languages as FORTRAN, C or even MAXIMA language.

More over, CARMEN is also able to communicate with other codes home code like CARMECA[1].

CARMEN is under development in the frame of the MINOS project [2] and its development started with CARINS in 2009. The development of a second version of CARINS is currently being completed and all the features of CARINS will be presented in the paper along with simulator results compared to hardware tests. Then CARDIM was developed between 2007 and 2009, in order to replace CARAMEL [3], a similar tool developed in the 90's. The new born in the family is CARSTAT and its development is just beginning. CARSTAT is based on CARINS experience and its basic principles will also be discussed in detail in this paper.

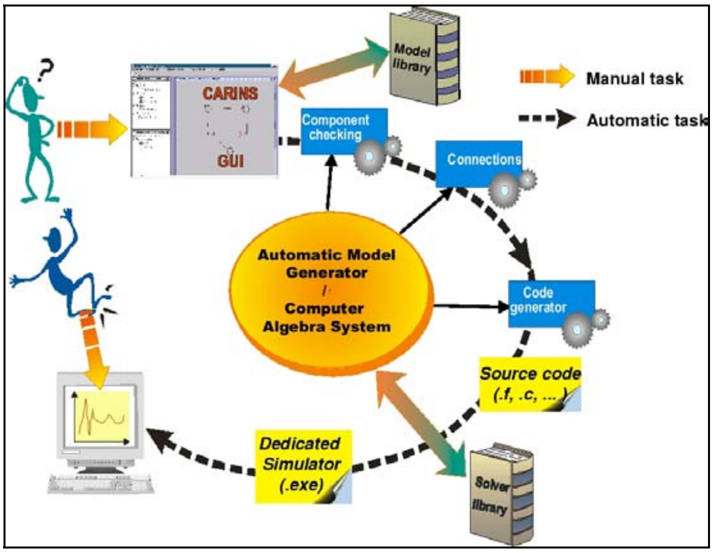

Figure 2 – Operating mode common to CARMOT, CARSTAT and CARINS

2. CARFONC

2.1. CARINS

2.1.1 Presentation of CARINS

From 2002 to 2005, CNES DLA, along with ONERA, APPEDGE, CAPGEMINI and several university laboratories, developed the open software CARINS [4,5]. CARINS is a versatile and flexible tool for reproducing time evolution of physical parameters which characterize the behavior of space propulsion systems or sub-systems, especially during transient phases. It can be used in future project phase as well as for ground tests or flights analysis.

From 2006 to 2009, a new version of CARINS has been developed, including a new graphic user interface, new models and new features.

Thank to its architecture based on MAXIMA as described in introduction, CARINS is able to simulate all systems that can be described with ordinary differential equations or algebraic equations. Moreover, CARINS also has the ability to use co-simulation for other problems.

CARINS relies on its library of high level physical models, which are developed by ONERA, LML (Laboratoire de Mécanique de Lille) [6,7], LFCT (Laboratoire des fluides complexes et thermique) and LEMTA [8] (Laboratoire d'Énergétique et de Mécanique Théorique et Appliquée) laboratories. Among other, this library contains the following models :

- transients models of pumps and turbines,
- combustion chambers taking into account chemical kinetics and droplets evaporation (for non ideal or ideal perfect gas),
- cavities, orifices and 1-D cosimulated non adiabatic pipes are available for ideal perfect gas, non-ideal perfect gas, real gas (e.g. Benedict-Webb-Rubin law), and two-phase flow,
- 1-D axisymmetric tank using co-simulation

CARINS also offers several tools based on SCILAB to perform further studies with the help of the graphic user interface. Parametric studies and sensitivity analysis are available, along with an optimization module to carry out identification of our simulators on tests results.

2.1.2 Some example of realizations with CARINS

This paragraph proposes a review of some of the system transient simulators that are available or under development at CNES Directorate of Launchers..

2.1.2.1. Vulcain 2 engine start-up

The Vulcain 2 simulator in CARINS has been developed using models from CARINS main library but also dedicated models specially created for it through the graphic user interface of CARINS, before the newest models were available. Figure 3 shows how the engine looks in CARINS and figure 4 shows the computed oxygen turbopump rotational speed compared to ground test results. The computation time for this simulation is 4 min.

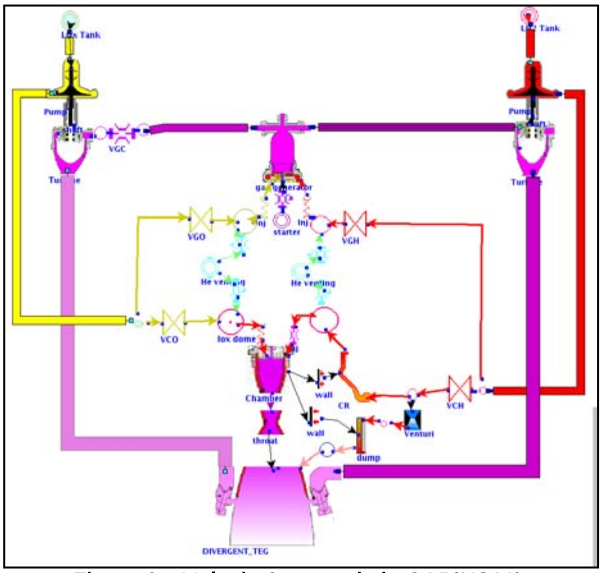

Figure 3 – Vulcain 2 synoptic in CARINS V2

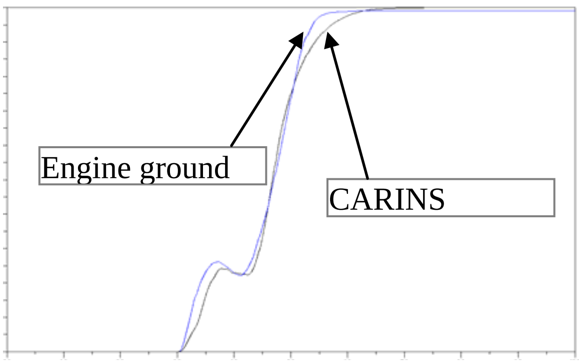

Figure 4 – Vulcain 2 oxygen pump rotational speed

2.1.2.2. EPC stage simulator

Two versions of ARIANE 5 cryogenic main stage simulator have been developed with the first version of CARINS, one for the Ariane 5 Generic configuration and the other for Ariane 5 ECA configuration. Both simulators have been compared to flight measurements and give very good results except for the temperature of the Helium high pressure capacity which was modeled as a perfect gas since the real gas model was not available at that time. Figure 5 shows some of the results compared to ARIANE 5 flight measurements. The computation time is less than 15 minutes for several hundred seconds of real time. This model is to be assembled with the Vulcain 2 engine simulator.

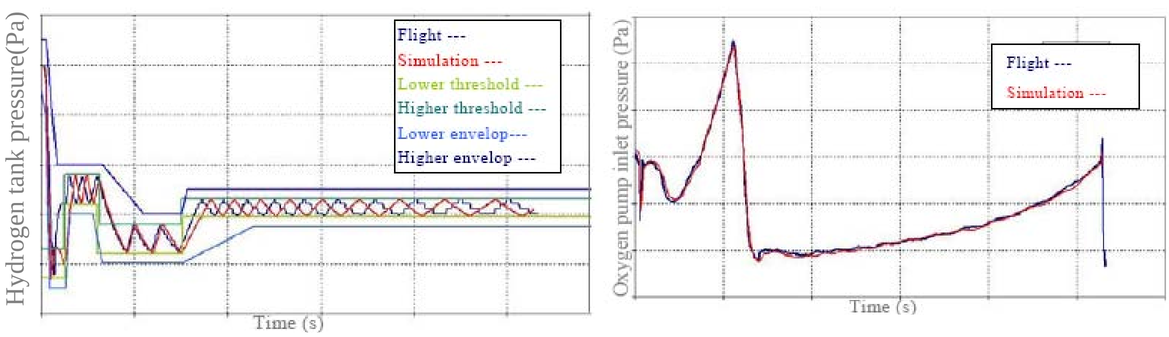

Figure 5 – EPC hydrogen tank pressure and oxygen pump pressure

2.1.2.3. SCA-VUS for ARIANE 5 ATV mission simulator

For the delivery of the Automated Transfer Vehicle, ARIANE 5 hydrazine attitude control system (SCA) had to be modified and requalified for long duration mission. The dedicated version of the attitude control system is called SCA-VUS for Versatile Upper Stage. Thanks to CARINS, cross-checks of ground tests and flight predictions have been possible. Figure 6 shows the comparison between CARINS and TMM flight predictions.

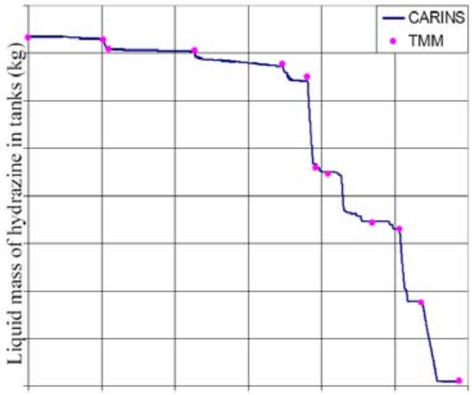

Figure 6 – SCAVUS liquid mass of hydrazine in tanks prediction

2.1.2.4. Other available simulators

Among our other CARINS simulators the most advanced ones are VULCAIN, VINCI, and HM7B engines, VEGA launcher's AVUM stage, and KVD-1 LOx-Methane engine. VULCAIN and HM7B engine simulators show good results for start-up transients. VINCI engine simulator is very robust and has less than 3% of error on 8 different steady operating points. AVUM stage simulator includes pressurization system, tanks, lines and the MEA engine and has served to determine the domain of pressure and temperature at engine inlet during "hot" missions or "cold" missions, taking into account external thermal fluxes (convection and radiation). KVD-1 simulator [9] has served to reproduce ground tests done in cooperation with Russia [10].

2.1.3 Conclusions

CARINS is now widely used by CNES DLA propulsion engineers. Its easiness of use and reliability allow them to create optimized and dedicated simulators on demand at sub-system or system level, with good reactivity.

Future development of CARINS are also planned, including coupling CARINS with 3-D codes or enlarged real fluid thermodynamics tables.

2.2. CARSTAT

2..2..1. Presentation of CARSTAT

CARSTAT will be the tool dedicated to steady state operation analysis and prediction.

It will allow to simulate steady state operations, engine tuning, but also limit, extreme and qualification domains.

Thus, CARSTAT will be used from future project state (calculation of operating points of engine designed by CARDIM) to the exploitation phase (operating points prediction, domain analysis).

CARSTAT will be able to dialog with CARDIM and CARINS but also with codes external to CARMEN like domain analysis code CARDOM, following the flux diagram shown on figure 7.

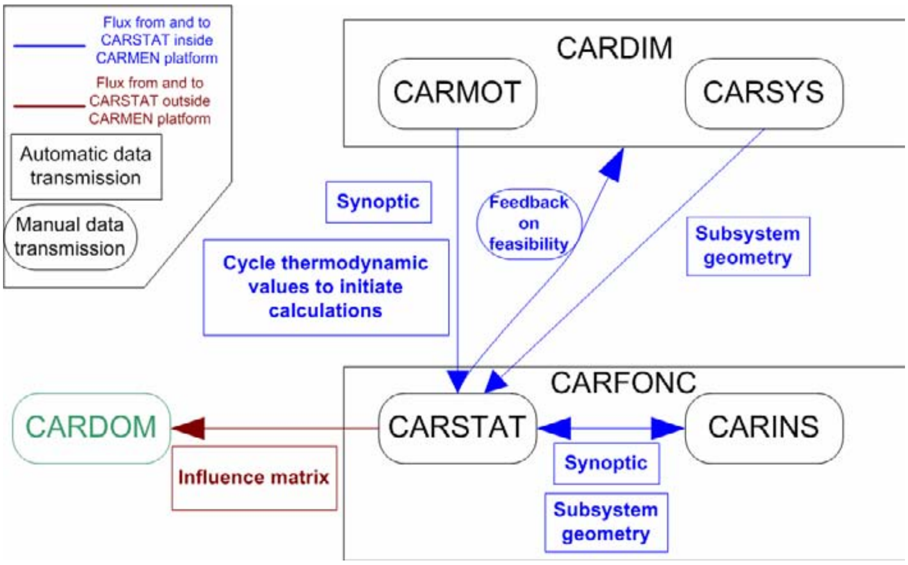

Figure 7 – Flux diagram of exchanges between CARSTAT and the other codes

Like CARINS, CARSTAT will be able to do parametric studies, sensitivity analysis and parametric identification.

2..2..2. CARSTAT strategy

In most cases, software meant to simulate steady state operation are based on iterative solver using methods Newton methods.

The experience acquired with CARINS has shown that CARINS solvers (LSODA, LSODES) are very efficient.

The time taken by those solvers to reach stabilized regime essentially depends on stiffness of the equations system to be solve, that is to stay, physically speaking, on physical events with short characteristic times.

The aim of CARSTAT is to reuse CARINS physical models and solvers and to reduce their stiffness in order to reach stabilized regime solution as soon as possible. This will be done by modifying physical models to suppress rapid phenomenon while keeping exact solution for steady state. Thus, the transients observed with this models will have no more physical signification but will be a mean to reach rapidly the steady state solution.

Apart from the very short simulation time expected with this method, the use of this strategy will be transparent for the user, which will only be given the steady state solution. However, the user will also be able to observe the "mathematical transient" if he wants to, specially if he works on personal physical models.

2..2..3. Conclusion

CARSTAT tool will be based on an inventive methodology, benefiting from CARINS experience, which consists in transforming the physical transients of existing models in a mathematical transient. This method should be able to give very fast and reliable simulations.

3. CARDIM

3.1 Introduction to CARDIM

Following the success of CARINS development CNES, with its partners APPEDGE and CAPGEMINI, decided to develop a new software dedicated to the preliminary design phase of an engine.

Developed between 2007 and 2009, CARDIM employs the same informatics as CARINS. It is composed by two main modules: CARMOT for the calculation of engine thermodynamic cycle and CARSYS for the preliminary geometric design of the subsystems providing a practical tool for concurrent engineering design approaches.

CARDIM offers a complete set of thermodynamics models for the engine cycle calculations (CARMOT) and a library of advanced design modules for subsystems design (CARSYS). These last ones are developed in parallel by the specialist and customised for use in CARDIM. They are respectively:

- creapom and creatur for turbopumps design
- chambi for thrust chamber and injectors
- dragon for nozzles
- dimether for regenerative circuits

As in CARINS, the user can easily create and manage his own models directly via the graphic interface thanks to the personal libraries.

Back into the CARMEN design logic, once the engine preliminary design is completed in CARDIM, the geometrical data of the subsystems are transferred to CARINS (or CARSTAT) for the transient behaviour as well as to CARMECA [1] for preliminary mechanical analysis.

3.2 CARDIM: test case

In this section are shown the results for the CARDIM design of the Vulcain engine, previous main engine of Ariane 5. Starting on the overall system specification CARDIM allows to get a first preliminary design of the cycle and the sub-systems.

References	
Thrust	1025 kN
Pc	100 bar
Pc (gaz generator)	77.4 bar
Tc max (gaz generator)	870 K
RM chamber	5.9
RM Gaz generator	0.9

Table 1 INPUT data for the Vulcain engine

The thermodynamic scheme of the engine is build in the CARMOT interface. A set of initial guess for the unknown parameters is imposed. The VULCAIN thermodynamic model presents 155 variables and a total of 58 equations. The simulator provides the system solution in about a minute.

	Reference	CARDIM data	Delta
Vacuum thrust kN	1025.0	1024.3	<1%
Vacuum Isp	433.3	433.53	<1%
Hydrogen turbo-pump			
W MW	10.3	10.29	<1%
Oxygen turbo-pump			
W MW	2.8	2.8	<1%

Table 2 CARMOT results and reference values for the VULCAIN engine

The subsystem design part is done with CARSYS, here the main subs-systems are shown.

	results vs real data (%)
Chamber body	
Throat Diameter	-6 %
Chamber Diameter	-2 %
Total chamber length	+1 %

Convergent angle	-3 %
Injectors:	
Number of elements	-12 %
Mass flow per element	+11 %

Table 3 Comparison of the geometrical results for the combustion chamber

The results give estimations of the real geometry with a maximum difference of 10%: this depends on the answers and values assigned by default to the module. This approach is meant to provide a first approximation of the design and it is always possible to refine the results using the single module in its complete version.

	Ref	CARDIM	results vs real data (%)
No of centrifugal stage for TPO Pump	1	1	0
No of centrifugal stage for TPO turbine	1	1	0
Rotational speed TPO rpm	12530	12530	0

Table4 Comparison of results for the Oxygen turbine

The nozzle detailed profile is sketched via the module DRAGON. Below the results obtained.

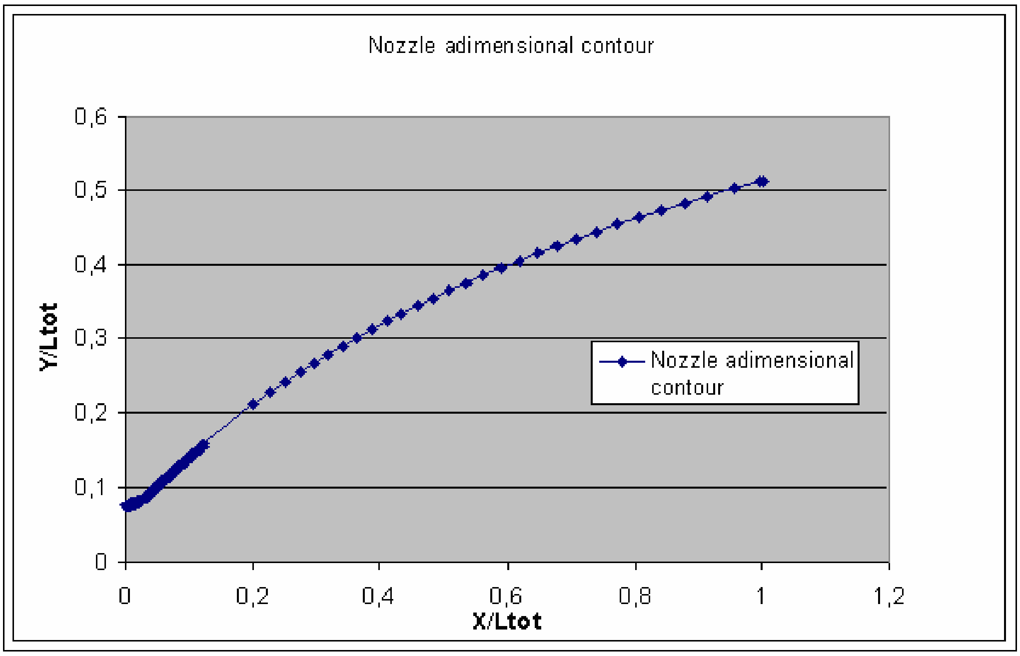

Figure 8 Nozzle contour results

	results vs real data (%)
Divergent length	+6 %
Exit diameter	+ 5 %

Table 5 Comparison of results for the divergent part

The design obtained can be further improved via the refinement of the parameters of each particular module of CARSYS, but still provides representative calculations of the engine functional performances and constitutes a basis for comparison and further analysis.

4. CONCLUSIONS

Once the engine preliminary design is completed, the geometrical data of the subsystems can be used in CARFONC to obtain the steady state or transient behavior, but also in CARMECA for preliminary mechanical analysis.

CARMEN softwares are linked together and each output file can be exploited in various forms. The entire cycle of analysis of an engine is practically implemented in a common and unique informatics environment.

5. REFERENCES

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