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CARINS : A versatile and flexible tool for engine transient prediction
Development status

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Abstract

CARINS is a new versatile and flexible tool for simulation of liquid propellant rocket engine systems transients. This kind of numerical simulation can reduce drastically design development costs and checking capacities.

The goal of the project is to give to engineers and research teams a new powerful tool for reproducing time evolution of physical parameters which characterise the propulsion system behaviour for space launcher, or only part of it, during all the mission phases (start-up and shutdown transients, chill down phase, operating point modification, …). This project was initiated four years ago by CNES, in partnership with ONERA, and it involves several laboratories. The first version will be qualified in summer 2004.

For this project, CNES included two extra items which make uniqueness of CARINS : first, the tool must be an open software and second, the software must be free of licensed-tools. That is why we choose a symbolic manipulation offered by Computer Algebra System and numerical analysis for computing the response of a dynamical system.
First applications are presented specially on ARIANE 5 stage pressurisation sub-systems, VINCI hydrogen turbo pump axial equilibrium system, HM7 and AESTUS engine transient and VULCAIN combustion components.

1. Introduction

CARINS is a versatile and flexible tool for engine transient prediction in liquid rocket propulsion. This project was initiated four years ago by CNES, in partnership with ONERA, and it involves several laboratories [1]. The project is part of the French national research and CNES Launcher Simulator Program.

Although numerical simulation is more and more used to predict operation of practical systems, it remains one of the main challenges of next years. In many fields, simulation will reduce drastically design development cost. For instance, simulation can built digital mock-up of systems in order to :

- understand static or dynamic behavior ;
- conduct damages tolerance tests for critical applications when only “virtual” design is available, and to prepare test campaigns for real hardwares ;
- conduct parametric studies in order to choose optimal design.

The objective of the CARINS project is to give to engineers and research teams a new powerful tool for reproducing time evolution of physical parameters which characterise the propulsion system behaviour for space launchers, or only part of it, during all the mission phases (start-up and shutdown transients, chill down phase, operating point modification, etc.).

Several attempts have been made to use commercial softwares for liquid propellant rocket engine (LPRE) studies. But in many cases, the goals were not totally achieved because, either physical models were not implemented, or it was too difficult to implement them in the requested time. So, CNES had already participated in such software developments in the 90’s. For the new tool, in addition to usual specifications, CNES included two extra items which make the uniqueness of CARINS : first, the tool must be an open software where the users will be able to operate easily at the lowest level of programming for new models development, and second, the software must be free of licensed-tools, in order to control as much as possible the CARINS development and future upgrades, and to easily distribute the software to its partners, as research laboratories, if necessary.

Moreover, the software structure must take into account complex physical phenomena involved in LPRE transients.

2. General Description

Background and architecture of CARINS

CARINS is structured around three main entities, whose development will allow to meet the goals below :

- an easy-to-use graphical user interface (GUI), realised using a object-oriented method ;
- a model library : basic element models are organized under mathematical structure (state variables, internal variables, parameters, equations) which will ensure their generic status and gives to the software the best evolution capabilities. This structure is obtained by building models from general laws of energetic and mechanics. Parameters are used to describe physical phenomena of smaller scale ;
- an Automatic Model Generator (AMG) using a computer algebraic system under GNU license (MAXIMA).

The engineer describes his system through CARINS's GUI (see Fig. 1 and Fig.2 in Annexe) in which he can enter numerical data or analytical formulas built upon variables or expressions that are part of the system. These inputs must be specified in the MAXIMA syntax form.

After the system modelling is completed and checked, the MAXIMA Computer Algebra System (CAS) performs the scheme analysis (interconnection) to build an optimised set of equations and then automatically generates a numerical Fortran simulator of this system.

Such kind of software, combining GUI and CAS, allows to manipulate not only numbers but formulas, equations, mathematical expressions and user expressions. So the modelling task can be viewed as the CAS customisation to a specific engineering domain using the GUI. Coding of formulas provided by the user is also done by such a software, as he can learn how to translate mathematical expressions into numerical languages.

The last step is to automatically generate the optimised code of the simulator that is then linked with a solver of ordinary differential equations (ODE).

Physical models

Liquid propellant rocket engines systems to be considered varies from simple pressurised engines of low thrust for satellite applications to complicated stage combustion cycle engines for heavy launcher applications. Every LPRE system can be viewed as the assembly of a lot of components such as tanks, pipes, valves, orifices, vessels, pumps and turbines, injectors, combustion chamber for gas generator or main thrust chamber, nozzles, etc.

In these components, very different thermo dynamical conditions and physical phenomena are observed during engine operation. Propellant can be liquid at low temperature in cryogenic tanks or hot gas in combustion chambers. Two-phase flows can be encountered in regenerative circuit where the liquid and its vapour are present ; inert gases can be melted with liquid propellants during chill down sequence. Besides the fluids, mechanical pieces are subject to strength and movements like pump rotors and regulator pistons for instance. Nevertheless, the propellant flows and the mechanical movements obey to general conservation laws. So, physical models will have to reproduce the correspondent compliant, inertance, resistive and propagation effects.

Nevertheless, characteristic times are of primary importance in transient simulation and modelling can take advantage of this point. For instance, if one is interested in water hammer effect due to rapid valve opening, where the inertance and the compliance of the fluid are combined to lead to wave propagation, one dimensional model is required with partial differential equations. In other application with slower transient, the liquid can be modelled as incompressible fluid. In this case, the lumped parameter method, solving ordinary differential equations, is accurate enough. Moreover, for some applications like chemical kinetics for instance, the characteristic times may vary. Thus, simulation tools should take into account all these various situations, and also those not yet imagined.

However, simulation requires two steps from the engineer’s point of view. The first one is the modelling, including the choice of the relevant model for every component of the process and the assembly of these components. The second one is the resolution of the problem.

Simulation phase

The main characteristic of the generated simulators is its efficiency because it is specific to the studied system. Dedicated simulators perform a more accurate and more efficient simulation than “black box simulators".

For each modelled process, MAXIMA generates a global virtual code (before the effective code generation), which is translated into Fortran with a MAXIMA Fortran generator . The virtual code generation brings flexibility into the building of the simulator : then one can solve the system with the solver of his choice.

CARINS offers LSODA (Livermore solver for ordinary differential equations, with automatic method switching for stiff and nonstiff problems) and LSODES (Livermore solver for ordinary differential equations with general sparse jacobian matrix) solvers and linpack library to solve the ODE system. Other solvers will be added to CARINS in the future.

CARINS is able to handle many kinds of discontinuities by zero crossing detection. Few software packages are able to correctly compute these types of discontinuities or to implement effective integration methods for such situations. The common turnaround is to smooth discontinuities. This smoothing approach leads to artificially stiff systems and introduces higher derivatives.

MAXIMA is a helpful parser to really identify the discontinuities functions (sign, timer, logical statement, ..) and to improve the differential equation system organisation for accurate root finding problem, that is switching points localisation.

To sum up briefly, the heuristics of integration strategy is based on the definition of Boolean electronic components: D-type with flip-flops with clock enable and D-type transparent latches. The switching functions keep the value they have at the last validated step during the computation of the next step by the solver. Thus, the ODE system has a continuous representation and the numerical resolution is very fast. If no discontinuity flag is set, the new step is validated, the switching functions are updated and computation goes on. When a discontinuity flag is set, the switching point location procedure starts until it is found with a given accuracy. After the event is processed, the new step is validated and the integration is restarted with the new ODE system.

The main advantage of this method is that it may be applied to any integration methods for ODE systems.

3. Development status

Background

Development of CARINS began in 2000 and was made by a serial of four prototypes, each one complete the latest and follows specific phases: definition, conception, programming, integration, validation.

Moreover the fourth prototype corresponds to the first version of CARINS and will be operational this summer.

This method allows a good evolution of the tool between specification and application.

During development, laboratories and CNES has tested all the functions of the tool and begun to use it for specific application.

Rocket engine transient

One complete rocket engine of ARIANE 5 Launcher have been built : HM7B (synoptic is show in Fig.3).

This rocket engine was used on the third stage H10 of ARIANE 4 and will be used on the second stage ESCA of ARIANE 5. It is operating with a gas generator cycle (open cycle) with liquid hydrogen and oxygen cryogenic propellants.

First task is to simulate the start up transient of the HM7B engine.

Two liquids are used : liquid hydrogen and oxygen from the tank.

Five gas are used : hydrogen and oxygen gas from the vaporization phenomena, water vapour from the combustion process, helium gas for the ventilation, powder gas for the starter and igniter.

Model represents the system engine from the outlet of the tank to the nozzle exhaust. Opening and closing valves are controlled by instruction orders with an evolution of the opening or closing in time.

Chamber is a combustion reactive and mixing cavity. Regen cooling line incorporates a two phase flow model.

Valves and starters opening and closing order are define.

Fig. 4 shows the evolution of the main pressures.

This test combines time response of valve handling, combustion reaction, turbo pump action. Results are quite close to the real hot fire test data. In particular, combustion pressure evolution presents good phenomena like overshoot.

Pneumatic system

D50 is the regulator of the EPS stage pressurisation system of ARIANE 5. A bottle of high pressure helium gas of 170 litre, 227 bar is opened throw the regulator to submit a constant exhaust pressure of 23 bar. D50 model uses mechanical and pneumatic components. In particular, mechanical equation is applied to the movement of the valves depending the pressures in the system and opening section depending of the position.. All theses equations are introduced by the GUI.

The difficulty of this test is to solve very stiff differential system because mass flow of the valve evolves quickly from a high value to low values and conversely.

Fig. 5 shows the pressure decrease of the bottle.

Fig 6. shows the regulator outlet pressure with a small variation of 250 mbars and a mean value of 23 bar.

Dynamicy study

Dynamic studies were made on a hydrogen turbo pump secondary flow of the VINCI rocket engine. This flow goes from the back of the secondary pump stage through the bearings and shaft to the back of the first pump stage. All this line is built by hydraulic elements and a dynamical equation for the position of the moving shaft. Rotation speed of the flow back to the disk are the equilibrium ones. With the tool we can observe the evolution of the system around the equilibrium position.

The study was made with a special function of CARINS which can calculate the influence of one parameter on variables. In particular, impact of the resistance (line length) or capacity (cavity volume) to the rotor position are investigating.

We performed also works on dynamical response of the system and frequencies studies. With a special modification of the system (decreasing of one volume in a cavity) we can afford good perturbation reject and pursuit, see Fig. 7 .

Regulation

CARINS offers to make regulation on rocket engine system.

For example : valve opening section can control a pressure in the system between upper and lower limit (see Fig.8).

4. Conclusion

The objective of the CARINS project is to develop a new generation software able to simulate LPRE transients. It is intended to be used for a large variety of engine cycles and propellants. In this paper, we presented the methodology, the structure of this tool and the firsts applications. Development status is almost finished and the tool will be operational this summer 2004 for engineer supporting ARIANE 5 program. CARINS is designed to be a powerful tool to fulfil industrial needs. It will increase flexibility in mathematical information management and end-user benefits.

The use of this kind of software will probably increase during the coming years as it allows research teams to test easily new physical models and it facilitates transfer to industrial users.

References

[1] Ordonneau G., Albano G. and Masse J. « CARINS : a future versatile and flexible tool for engine transient prediction », 4th International Conference on Launcher technology « Space Launcher Liquid Propulsion », Liège (Belgium), 3-6 December 2002.

Annexes Figures

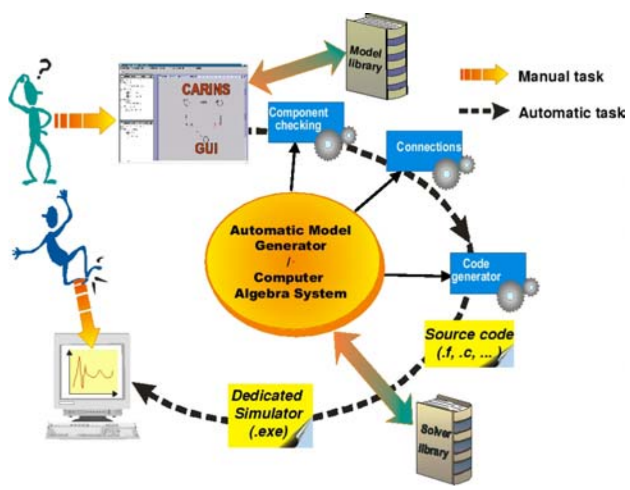

Figure 1 : CARINS Structure

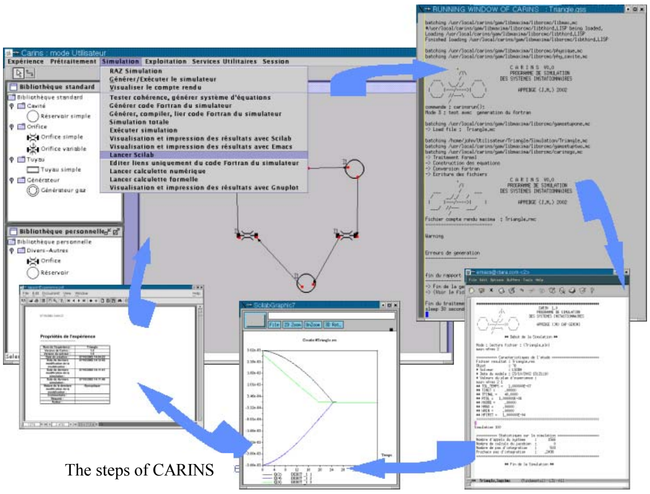

Figure 2 : simulation loop

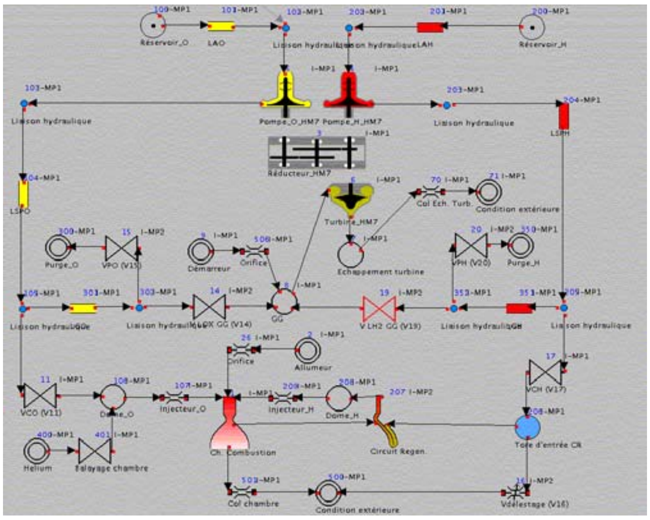

Figure 3 : synoptic of HM7b model in GUI CARINS

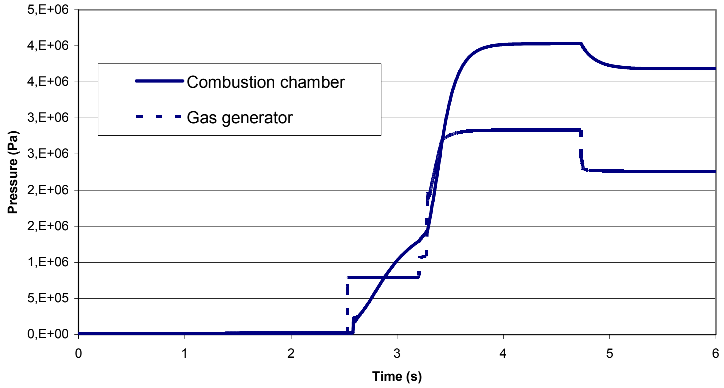

Fig 4 : Combustion Pressure

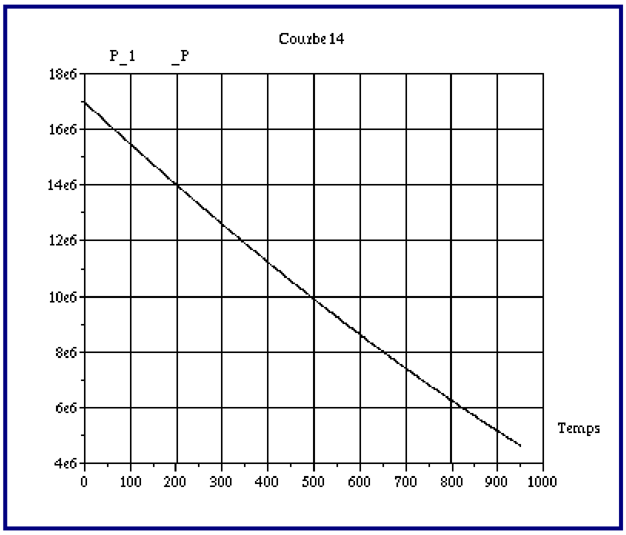

Fig. 5 Pressure in the bottle

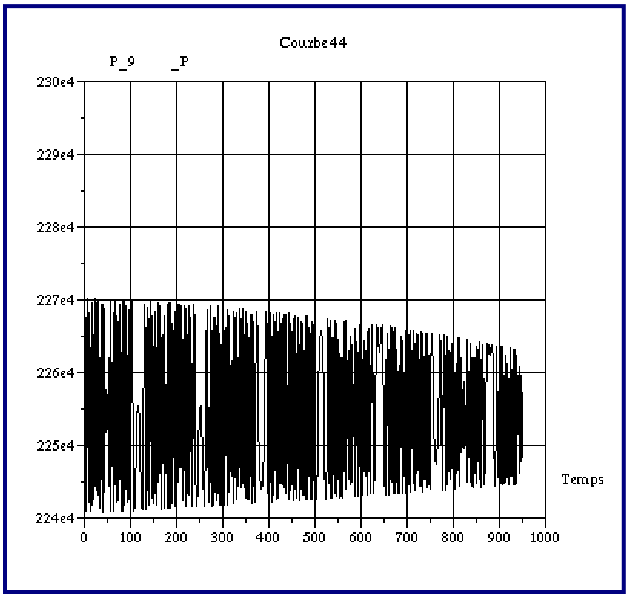

Fig 6. Regulator outlet pressure

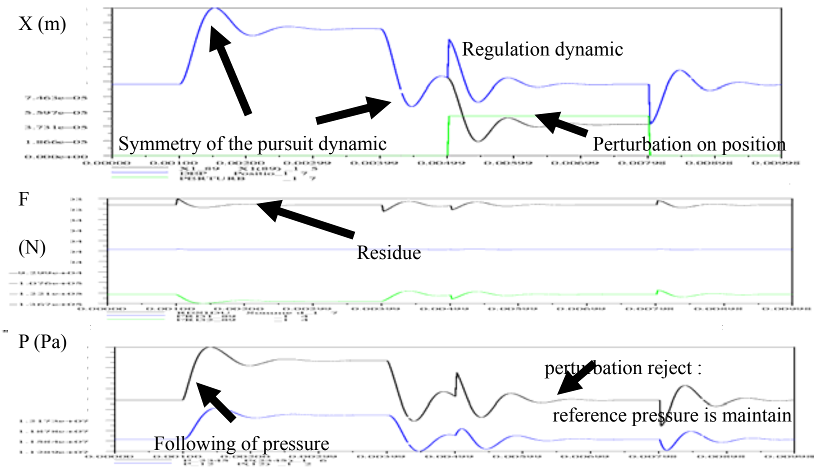

Figure 7 : perturbation reject and pursuit for turbo pump secondary flow

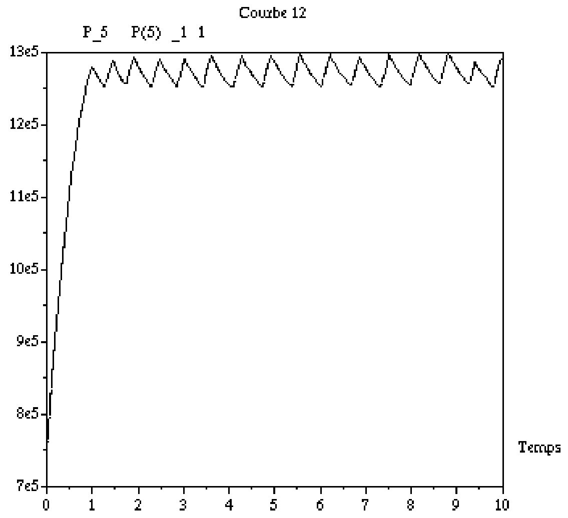

Fig. 8 : pressure evolution between two limit (13 bar and 12.5 bar)