HM7B ENGINE TRANSIENT SIMULATOR WITH CARINS TOOL

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CARINS is a new versatile and flexible tool for simulation of liquid propellant rocket engine systems transients. Systems are composed by pneumatic, hydraulic, mechanical, thermal and combustion subsystems. This kind of numerical simulation can reduce drastically design development cost, checking capacities and in future can be used for health monitoring system in reusable rocket engine.

This new powerful tool for reproducing time evolution of physical parameters characterizes the propulsion system behavior for space launcher, or only part of it, during all the mission phases (start up and shutdown transients, chill down phase, operating point modification, main stage,…). This project was initiated four years ago by CNES, in partnership with ONERA, and it involves several laboratories.

For this project, CNES included two extra items witch make 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. That why we chose a symbolic manipulation offered by Computer Algebra System and numerical analysis for computing the response of a dynamical system. Moreover, the software structure must take into account complex physical phenomena involved in LPRE transients and in particular the characteristic times of components.

The general concept of CARINS combines useful Graphical User Interface with "black-box" and Computer Algebra System (CAS) with symbolic manipulation. This allows manipulating not only numbers but formulas, equations, mathematical expressions and user expression. So the modeling task can be viewed as the CAS customization to a specific engineering domain using the GUI. Coding of formulas provided by the user is also done by such software, as they can learn how to translate mathematical expression into numerical languages.

Here, CARINS is used for simulating HM7B engine transient prediction. Results are compared to real tests fire or flight results. HM7B engine performance can be predicted and damage tolerance test can be conducted.

Because of is high performance, CARINS HM7B simulator is an executable so can be used as it for future application in a health monitoring system.

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.

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).

After the code generation and his link with numerical algorithms, we use another open source software : SCILAB. It manages and embeds the simulator for plotting and providing the sensitivity analysis of model outputs with respect to independent parameters. SCILAB is used as robot enables to rapid integration of these simulators and automates their execution to accelerate the evaluation of many more design alternatives.

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.

HM7B Simulation

Background

A modelisation with CARINS Tool of the cryogenic HM7B rocket engine transient have been conducted (synoptic is show in Fig.1).

This 63 kN of thrust rocket engine was used on the H10 third stage of ARIANE 4 and is used on the ESCA second stage of ARIANE 5. It is operating with a gas generator cycle (open cycle) with liquid hydrogen and oxygen cryogenic propellants. Energy for the turbine rotation come from a gas generator. This turbine drives the two pumps with a reductor.

Modelisation

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

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. A accumulation model with vaporization phenomena is included in the oxygen chamber cavity. Regen cooling line incorporates a two phase flow model.

Valves and starters opening and closing order are define.

Start up scenario

This HM7B engine simulation begins at the end of the chill down phase. At this time, purge valves are opened and helium gas circulations are activated.

Start up scenario execution is :

- Opening hydrogen chamber entrance valve
- starter and igniters ignition
- closing purge valves
- opening oxygen chamber entrance valve
- closing helium circulation on oxygen dome and gas generator chamber
- opening gas generator entrance valves
- closing relieve congestion hydrogen valve

Validation

A comparison with a ground test fire have been conducted.

Chamber and gas generator pressure evolutions can be find in figure 2 and 3.

Result are quit good even for nominal values. We can observe the first bounce on combustion pressure due to combustion ignition and gas generator starter functioning and second bounce due to gas generator ignition.

Damage tolerance test

To anticipate engine damage test, the simulator can conduct several damage tolerance test : valve leakage, valve opening delay, change in igniter energy, …

For example, we study a chamber oxygen valve delay of 70 ms. Because of the delay, more hydrogen gas was accumulated wich conduct to a more severe combustion start up (see Fig 4).

Another example, if a long gas generator valve delay occurred, combustion will not start.

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 first application for a complete engine. The tool is operational since September 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.

Illustration is done by the transient simulation of HM7B engine. 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.

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.

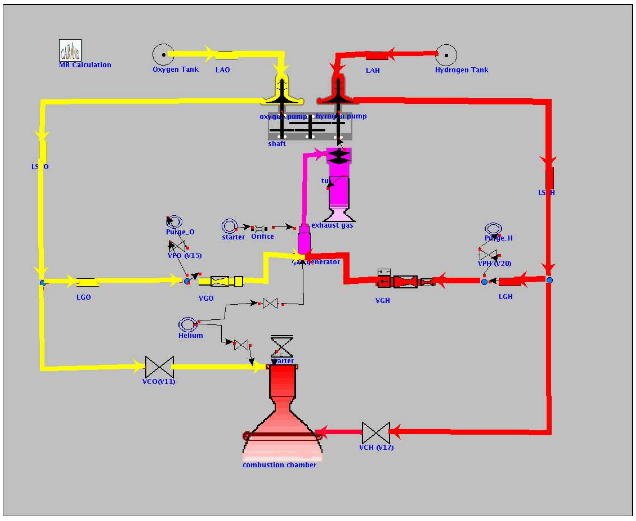

Figure 1

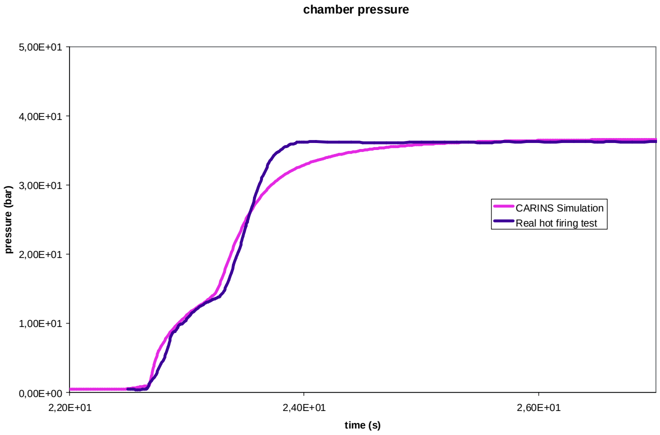

Figure 2

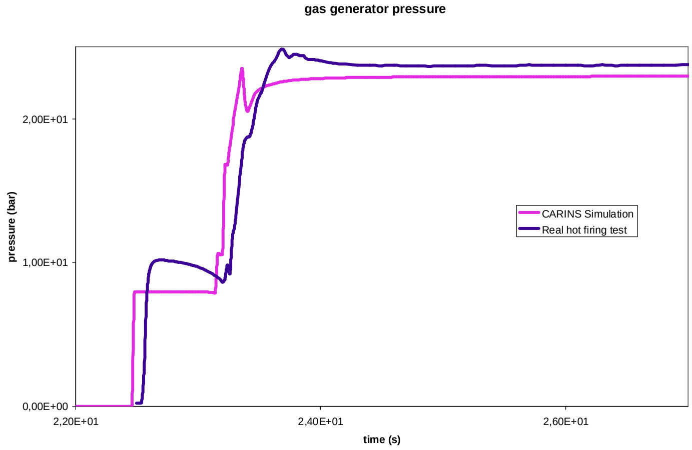

Figure 3

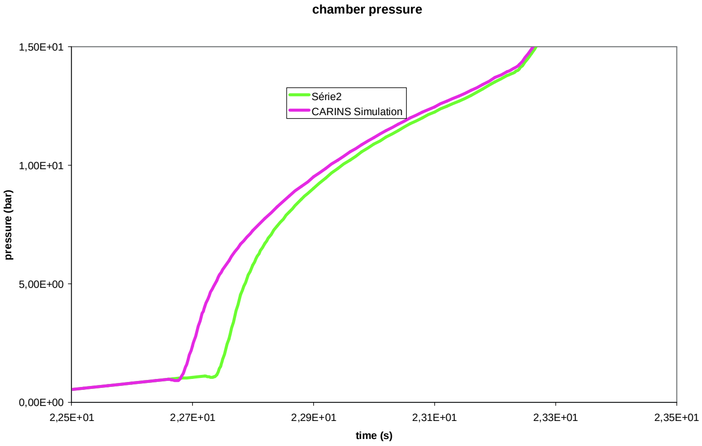

Figure 4