Development of 20 kN hybrid rocket booster

Alberto Bettella[§] , Federico Moretto , Enrico Geremia[§] , Nicolas Bellomo[*] , Dino Petronio[§] and Daniele Pavarin[*,**]*

**Department of Industrial Engineerinf University of Padua,*
Via Venezia 1 35100 Padova
***Center of Studies and Activities for Space University of Padua, Italy*
Via Venezia 15 35100 Padova
§HIT09 s.r.l., Padova, Italy

Abstract
A hybrid rocket booster was developed by CISAS "G.Colombo". The activity started from small-scale testing of lab motors and culminated on a successful testing of a demonstrator. The hybrid motor is propelled by self-pressurized nitrous oxide (N2O) as oxidizer and paraffin wax as solid fuel. The peak thrust is 20 kN, the total impulse 50 kNs and the N2O liquid phase burn time 3.5 seconds. The paper presents the design and development strategy applied

1 Introduction
RATO (Rocket Assisted Take Off) was used in the past to allow short take off of different type of airplanes. Currently it is applied on Unmanned Air Vehicle to avoid launch ramps or landing field, and big military aircraft during special operations. RATO systems are almost everywhere based on solid rocket boosters, which suffer from some management and safety issues: due to intrinsic level of danger, all activities concerning their handling shall respect the same rigid and demanding procedures as for explosive hardware or materials, which finally determine high management costs. Moreover solid rocket are not controllable at all.
Hybrid rocket technology could represent a valid alternative to the solid rocket one. In respect to solid rocket boosters hybrid technology provides increased safety when handling, transportation, storage and installation procedures are concerned: this applies in land and especially in naval operation, where stocks of explosive materials are highly avoided. These advantages determine a substantial cost reduction in procurement, integration and decommissioning activities. Moreover hybrid rockets are controllable and restartable thus allowing for a wider range of mission profiles respect to solid rocket systems.
CISAS (University of Padua) has performed a feasibility study in order to verify the possibility of developing a low cost hybrid rocket booster. CISAS development resulted in a prototype based on self pressurized N_2O/Paraffin, providing 50 kNs total impulse, 20kN peak thrust and 3.5 seconds burn time. This paper describes how the hybrid rocket was developed through ground testing of small, full scale battleship models and engineered light-weight aluminum-CFRP prototypes.

2 Development plan
The RATO booster was developed in the timeframe of three years, from sketch to final demonstrator. The activities included also the development of adequate facilities for small and full-scale testing and the engineering of the prototype.

2.1 Requirements
The following requirements have been considered as representative for the feasibility study: (i) total impulse greater than 50kN, (ii) gross weight of the booster lower than 45 kg, (iii) burning time between 3.5 and 5 s.

2.2 Design phases
The developed activity began with cold-flow testing of N_2O and the development of adequate quasi-steady models to predict the pressure unsteady behavior inside the tank. Subsequently more than 40 small scale tests allowed to verify design assumptions about grain, combustion efficiency, stability and motor operations (i.e. ignition and shutdown) and culminated with the definition of a satisfactory paraffin wax formulation.
23 full-scale (50kNs total impulse) battleship tests has been performed to scale up the motor and to setup the testing facilities. The main output was the casting procedure of 160 mm external diameter and 800 mm length grains, the combustion stabilization through proper injector plate design and the rise of combustion efficiency from 70-80% to more than 95%. Moreover, the burn time was changed "on the run" from 5 seconds to 3.5 seconds with only 2 tests.

Figure 1 Booster heavy prototype**.** The dimensions of the internal components (grain, pre and post chambers etc.) are identical to the final prototype. The external shell was manufactured from commercial cylinders.

At this point a "heavy prototype" (Figure 1) was developed with a finalized oxidizer valve and feed-line. A mechanical safety-control was placed on the valve and removed just before the launch to avoid accidental ignition. The valve stopped the oxidizer flow after the pressure in the tanks dropped below a specific threshold. The self-pressurization required the thermal control of oxidizer tanks before launch. 4 tests were required to setup the valve and ignition procedures.
Finally, in order to develop the Engineering Model, 10 more ground tests were carried out on the engineered motor configuration, with reduced weight valve and paraffin grain casted directly into the combustion chamber.

3 Motor design

3.1 System description

The RATO engineering model was constructed with lightweight materials: epoxy/phenolic carbon fiber, fiber glass, aluminum and high-tensile stainless steel. The total empty weight of the complete hardware was 42 kg. The resulting configuration is shown in Figure 2.
The combustion chamber is made by carbon-epoxy filament winding. The exhaust nozzle is fully integrated during the filament wrapping that acts as stress resistant structure. Pre and post combustion chambers are made by ablative materials.

Figure 2 – Booster structure

During the experimental campaign on this final version of the rocket booster every single component performed well, demonstrating a robust design; only minor adjustments were required after preliminary tests.
The intrinsic safety of the hybrid rocket technology resulted in cheap test facilities. Two different facilities have been used for performance verification, oxidizer discharge tests and full operational open-air firings, one to support small scale test and one to support open-air full scale experiments.

Figure 2 - CISAS open-air facility. This facility was used for the verification testing of the prototype motor. Each experiment was assembled/disassembled during the same test day, up to two tests/day.

3.2 Performance

The motor development has been specifically focused on: (i) the reduction of combustion chamber instabilities, (ii) the maximization of the combustion efficiency and (iii) the achievement of the required total impulse.
The preliminary test campaign showed a not stable behavior of the rocket. As it can be seen in Figure 4, three functioning conditions have been observed: an initial unstable phase of 0.5s, followed by a relative more stable phase lasting 1 s and a final very unstable phase of 3 s. The chamber pressure oscillates (50-60 % peak to peak, see Figure 3, on the right) in a very coherent fashion at a frequency of about 45 Hz. The combustion chamber pressure oscillations are also fairly regular in nature. The injector-upstream-pressure is also subjected to oscillations which were coherent with oscillations in the combustion chamber. Even though the injector pressure also participated in the oscillations, the wave forms are clipped at the lower end. This nonlinear behavior is commonly observed during feed coupled instabilities and is due to the coupling between pressure oscillations and mass flow rate. The oscillation frequency does not shift during the test, and its intensity is almost constant during the most unstable parts of the test. The initial increase of frequency is related to the pressure build up inside the chamber and the achievement of a (quasi) steady state mass flow. The FFT analysis also indicates that the feed system coupled instabilities completely dominates the transient behavior and the other low-frequency instability modes stay inactive for the entire test.
The problem was successfully solved with a new design of the injector plate.

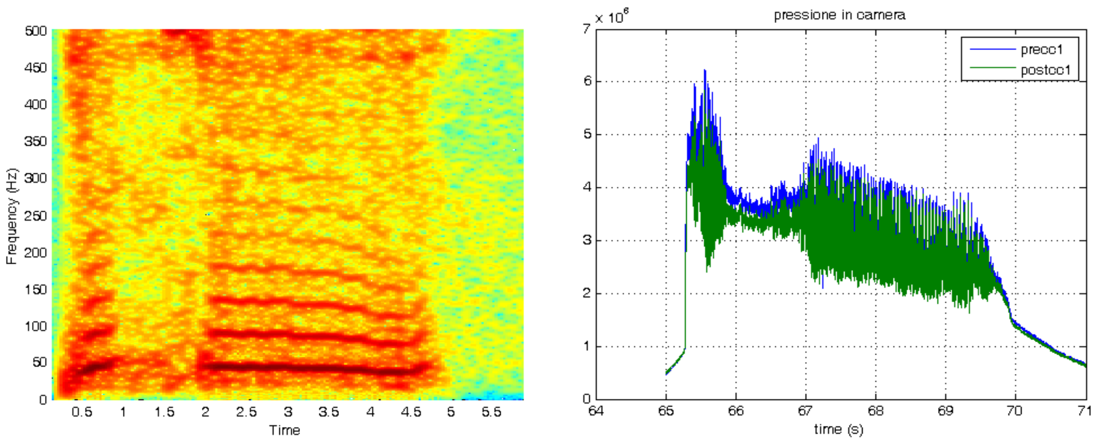

Figure 4 Pressure time history in the combustion chamber. On the left the spectrogram of the postcc1 signal, on the right the time history of pre-combustion and post-combustion chamber pressures. High feed-coupled instabilities were experienced and also resulted on the oxidizer tank pressure recording.

Preliminary tests showed a very low efficiency of the full rocket assembly respect to the small scale: the efficiency dropped to 75% from nearly 90%. Different chamber designs have been simulated using CFD codes: the focus point was the optimization of pre-chamber and post-chamber shape. The most promising configuration provided by numerical analysis has been manufactured and tested.

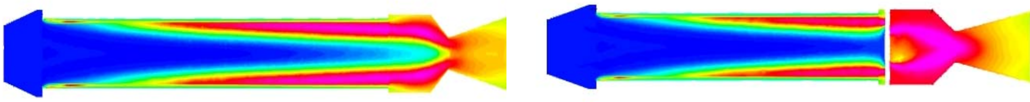

Figure 5 CFD simulation of the combustion chamber. Post-combustion chamber enhances the turbulence and mixing between cold oxidizer (blue colored core) with vaporized fuel. Pre-combustion chamber design has a moderate influence on the mixing too. The drawback is the added weight and the need to avoid mixer ablation. In this application, ablation was not an issue because of the short burn time required**.**

The optimization of pre-chamber and the post-combustion chamber allowed the achievement of high efficiency of the full scale rocket (96%).

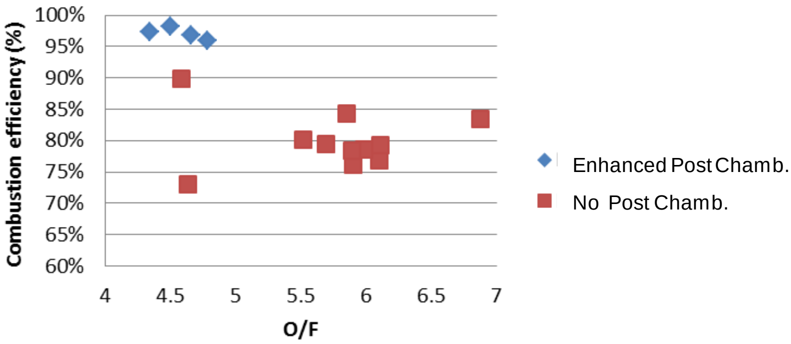

Figure 6 Combustion efficiency as a function of O/F ratio. Combustion efficiency strongly increased with the addition of suitable post-combustion chamber**.**

Last improvements regarded again the injection plate, developed during the second part of the project. This component has been modified to optimize the atomization/vaporization lag of the system and to reduce vortex shedding inside the pre-combustion chamber. It can be seen from Figure 7 that the motor is stable for almost the entire run, with the exception of the first 0.5 seconds. The initial behaviour is similar to previous tests but after 0.5 s the system switches from an unstable to a stable condition and oscillations never occur again. The frequency of initial oscillations is a bit higher (nearly 50 Hz). This means that the system is more "rigid" and this should explain why the instability disappears completely and doesn't reappear later.

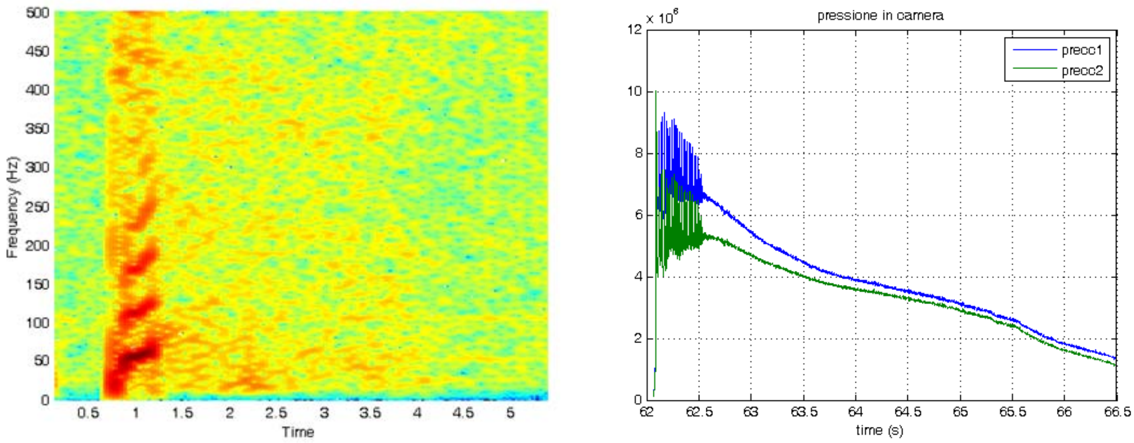

Figure 7 Time history of the pressure inside the combustion chamber**.** The injection plate has been modified to modify the vaporization lag and vortex shedding.

The last part of the project regarded the engineering version of the motor. Design modification has been related both to the ignition capability, that has been increased in power changing the solid cartridge ignition material, and to the design pressure inside the combustion chamber. The final design allowed for a stable and efficient combustion.

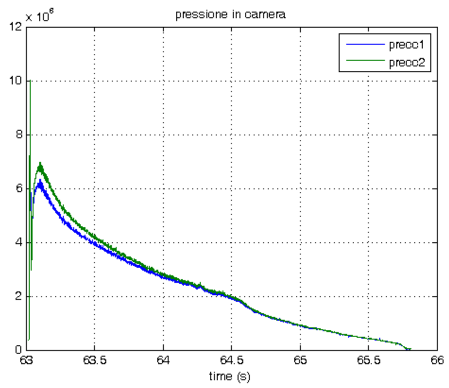

Figure 8 Time history of the pressure inside the combustion chamber. After modification of the ignition system even the initial instability has been reduced.

4 Conclusion

The development activity herein discussed shows that hybrid rocket engines can be a viable substitution of solid rocket engine in small booster applications.
The main advantage of a hybrid motor is the intrinsic safety that reduces storage, transportation and handling costs. Moreover the development is cheaper and substantial design changes can be made “on the run”. On the contrary, the design of hybrid engines suffers from lack in predictive methods, related to the regression rate primarily: experiments are needed to confirm design assumption and some adjustment is required after preliminary testing.

Acknowledgments

Authors thank Mr. Giacometti , Mr. Pertile and the municipality of Soverzene (BL) and Rossano Veneto (VI) , for their great support to experimental testing.

References

[1] M. A. Karabeyoglu, Greg Zilliac, Brian J. Cantwell, Shane DeZilwa and Paul Castellucci, “Scale-up Tests of High Regression Rate Liquefying Hybrid Rocket Fuels”, AIAA-2003-1162, 41st Aerospace Sciences Meeting and Exhibit, Reno Nevada, January 2003.

[2] Karabeyoglu, M. A., Altman, D., Cantwell, B. J., “Combustion of Liquefying Hybrid Propellants: Part 1, General Theory”, Journal Of Propulsion And Power, 2002, Vol.18; No. 3, pages 610-630.

[3] Karabeyoglu, M. A., Stevens, J., Cantwell, B., “Investigation of Feed System Coupled Low Frequency Combustion Instabilities in Hybrid Rockets”, 43rd AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, 8-11 July 2007, Cincinnati, OH.

[4] Carmicino C., “Acoustics, Vortex Shedding, and Low-Frequency Dynamics Interaction in an Unstable Hybrid Rocket”, Journal Of Propulsion And Power, Vol. 25, No. 6, November-December 2009.

[5] G. Zilliac, M. A. Karabeyoglu, “Modeling of Propellant Tank Pressurization”, AIAA2005-3549, 41st AIAA/ASME/SAE/ASEE Joint Propulsion Conference, Tucson, AZ, USA, 10-13 July, 2005.

[6] Dyer, J., Doran, E., Dunn, Z., Lohner, K., Zilliac G., B., Cantwell, “Modeling Feed System Flow Physics for Self-Pressurizing Propellants”, AIAA 2007-5702, 43rd AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, Cincinnati, OH, USA, 8-11 July, 2007.

[7] Chiaverini, M., “Review of Solid Fuel Regression Rate Behavior in Classical and Non-classical Hybrid Rocket Motors”, Fundamentals of Hybrid Rocket Combustion and Propulsion, edited by M. J. Chiaverini, and K. K. Kuo, Vol. 218, Progress in Astronautics and Aeronautics, AIAA, Reston, VA, 2007.

[8] Boardman, Terry A., “Hybrid Propellant Rockets”, Rocket Propulsion Elements, Seventh Edition, edited by Sutton, G. P., Biblarz O., Jhon Wiley & Sons, Inc., 2001.

[9] Jonny Dyer, Eric Doran, Zach Dunn, Kevin Lohner, Cedric Bayard and Andy Sadhwani, Greg Zilliac, Brian Cantwell and Arif Karabeyoglu, “Design and Development of a 100 km NitrousOxide/Para-n Hybrid Rocket

Vehicle", AIAA 2007-5362, 43rd AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit; Cincinnati, Ohio, USA, 8-11 July 2007.

[10] Jonny Dyer, Greg Zilliac, Eric Doran, Mark Marzona, Kevin Lohner, Evan Karlik, Brian Cantwell and Arif Karabeyoglu, "Status Update Report for the Peregrine 100km Sounding Rocket Project", AIAA 2008-4829, 44th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit; Hartford, CT, USA, 21-23 July 2008.

[11] Eric Doran, Jonny Dyer, Mark Marzona, Arif Karabeyoglu, Greg Zilliac, Robert Mosher, Brian Cantwell, "Status Update Report for the Peregrine Sounding Rocket Project: Part III", AIAA 2009-4840, 45th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit; Denver, Colorado, USA, 2-5 August 2008.

[12] M. A. Karabeyoglu, J. Stevens, D. Geyzel, B. Cantwell, D. Micheletti, "High Performance Hybrid Upper Stage Motor", AIAA 2011-6025, 47th Joint Propulsion Conference and Exhibit, San Diego, CA, USA, 31 July - 03 August, 2011.

[13] Altman, D., A. Holzman, "Overview and History of Hybrid Rocket Propulsion", Fundamentals of Hybrid Rocket Combustion and Propulsion, edited by M. J. Chiaverini, and K. K. Kuo, Vol. 218, Progress in Astronautics and Aeronautics, AIAA, Reston, VA, 2007.

[14] G., Story, J. Arves, "Flight testing of Hybrid-Powered Vehicles", Fundamentals of Hybrid Rocket Combustion and Propulsion, edited by M. J. Chiaverini, and K. K. Kuo, Vol. 218, Progress in Astronautics and Aeronautics, AIAA, Reston, VA, 2007.

[15] Altman, D. and Humble, R. "Hybrid Rocket Propulsion Systems" in Space Propulsion Analysis and Design, edited by Humble, R. W., Henry G. N., Larson, W. J., McGraw Hill, Space Technology Series, 1995.