

THRUST MODULATION ON A PARAFFIN BASED HYBRID ROCKET MOTOR

Carlos Alberto Gurgel Veras, gurgel@unb.br

Pedro Luiz Kaled da Cás, pedrokdc@gmail.com

Cristiano Queiroz Vilanova, c0617989@aluno.unb.br

Mechanical Engineering Department, Campus Universitário Darcy Ribeiro, Brasília - DF

Geovany Borges, gaborges@unb.br

Henrique Marra Menegas, henrique.menegaz@gmail.com

João Yoshiyuki Ishihara, ishihara@ene.unb.br

Electrical Engineering Department, Campus Universitário Darcy Ribeiro, Brasília - DF

Abstract. *This work presents experimental results of a small hybrid rocket motor capable of varying thrust by means of throttling or multiple shut off and restart cycles. For a given mission, hybrid rocket technology may become the best choice by virtue of its inherent advantages over more traditional chemical propulsion systems. Due to reduced development and recurring costs hybrid propulsion systems would be a fine alternative for countries and enterprises willing to enter the international space market. This research was based on liquefying fuels, such as paraffin, natural waxes and mixture of both, carried by the Hybrid Propulsion Team from University of Brasilia – Brazil. Thrust variation was accomplished by controlling the oxidizer flux to the combustion chamber. The liquefied fuel was obtained after mixing solid paraffin and alternative waxes with proper proportion for better structural solid matrix, while keeping high regression rates. Nitrous oxide was used as the oxidizer. Shut off and restart cycles were possible without the help of extra ignition source. Thrust variation was possible by controlling the oxidizer mass flux as well by on-off cycle.*

Keywords: *hybrid rocket, thrust modulation, paraffin wax.*

1. INTRODUCTION

In a review paper, Oiknine (2006) analyzed what have prevented hybrid propulsion from substituting solid and liquid technologies in commercial space applications, despite several inherent advantages over the classical counterparts, namely:

- Safety (in manufacturing, transporting and storage as a consequence of separate fuel and oxidizer);
- Reliability (due to the larger margin of tolerance in grain imperfections as well as ambient conditions);
- Flexibility (by virtue of stop-restart capabilities and thrust modulation);
- Costs (because of low investments costs for development and operation as well as those costs associate with the materials to fabricate de motor);
- Environment (since combustion products are, often, non-toxic gases and propellants are not hazardous to storage and transport).

Karabeyoglu (2008), however, claims that hybrid propulsion should be complementary to other chemical rockets, finding specific niches where safety and cost are more important than performance. Space tourism and small launch vehicle propulsion system are instances of such observation.

Unlike solid rockets, classical hybrid rocket motor, in which the fuel is solid and the oxidizer is liquid, may operate with varying thrust in a wide range of condition over some specific value. Also, by controlling the oxidizer mass flux, the performance of the system can be maintained optimized for a given mission, despite the variation on the solid fuel geometry. Rajesh (2006) described the design details of a hybrid rocket motor for a specified thrust time profile. Design requirements were 18 kN thrust for the first 5.5 seconds followed by a decrease to 8 kN in the remaining 4,0 seconds of the proposed mission. The propellants were nitrous oxide and HTPB (Hydroxyl Terminated PolyButadiene). The variation in thrust presented an adverse effect on the specific impulse, on account of the change in the O/F ratio. Decrease in combustion efficiency may also occur by oxidizer throttling but was not considered in the work [3]. An experimental study on thrust modulation in hybrid rocket engines was conducted by Waidmann [4]. Controllable, stable, and reproducible throttling properties were demonstrated down to 10% of thrust in a 500 N (maximum) motor burning RFNA (oxidizer) and mixtures of aromatic and cyclic amines (fuel). Throttling and restart capabilities of a small hybrid rocket motor were also demonstrated by Knuth et al. (1999) in a GOx (gaseous oxygen) and HTPB system up to 900 N thrust. Cavalleri and Loehr (2005) have demonstrated variable thrust capability by changing the oxidizer fuel ratio in a N₂O-HTPB hybrid motor.

Hybrid rocket propulsion has been extensively researched by our aerospace group since the year 2000 (Viegas & Salemi, 2000; Santos & Almeida, 2004, Almeida & Santos, 2005,

Most of the important features of hybrid propulsion systems, based on liquefying fuels, have been verified in previous works conducted by our group. Further research is now needed in order to explore other distinctive marks of hybrid propulsion technology. The main objective of this work is, therefore, to verify thrust modulation in a small hybrid motor. This goal was accomplished by varying the oxidizer mass flux to the combustion chamber and by a series of shut off and restart cycles, without the need of extra energy for ignition. The propellants were nitrous oxide and solid

paraffin. We also tested a new type of solid fuel mixed to the paraffin to improve some structural properties making sure the expected high regression rates should not be penalized.

2. LIQUIFYING FUELS AND N₂O SYSTEMS

Oiknine [1] emphasized the main cause of the commercial failure of hybrid motors to date: the low fuel mass flow. Different means have been proposed to increase the solid regression rate in hybrid systems (Knuth et al., 1999). Following that, new classes of fuel have been proposed such as those which form a melt layer before combustion, named as liquefying fuels (Cacarelli & Loehr, 2005). The high regression rate obtained in liquefying fuels was explained by the instability of the liquid layer that produces small droplets at the tip of the waves, induced by the gas flow inside the grain port. These droplets, from the melt layer, are entrained and burn via heterogeneous combustion in the oxidizer gas stream. Another interesting feature of liquefying fuel is regard to scalability effects. Experimental results from two different motor, 6.0 and 18.75 cm grain outside diameter showed regression rates quite similar for both motors (Karabeyoglu et al., 2004). Their work suggested the following regression rate law for the paraffin based fuel.

$$\bar{r} = (0.488) \bar{G}_{ox}^{0.62} \quad (1)$$

In (1), regression rate is in mm/sec and oxidizer mass flux is in g/cm²/sec. Also, the correlation was obtained with the mass flux of oxidizer varying from 5.0 to 40.0 g/cm²/s, thus, showing a less problematic scaling effect of liquefying fuels if compared to classical hybrids fuels, e.g. HTTB.

In a set of experiments conducted by our research team, at very high nitrous oxidizer mass flux ($\cong 50$ g/cm²/s), we estimated mean regression rates higher than 9.0 mm/s, for paraffin based solid fuel [8]. The initial port diameter was 26 mm for which the initial oxidizer mass flux was above 140 g/cm²/s. Liquid nitrous oxide was injected into the combustion chamber by means of a series of pressure swirl atomizers. Average regression rate as high as 6.73 mm/s was also reported in Rajesh (2006) using gaseous oxygen (initial G_{ox} of the order of 100 g/cm²/s).

Figure 1a shows a thrust curve against time for one such experiment, with a 1500 N design thrust. This engine was designed to power a small sounding rocket based on N₂O and paraffin system for about 10 seconds. The prescribed rocket apogee was set to 6000 meter and it was, basically, made of aluminum alloys and advanced plastic materials. The maiden flight of this rocket is planned to 2010, after the rocket motor passes the qualification static test. In Fig. 1, oxidizer tank was filled with nitrous oxide to sustain the burning for no longer than three seconds. Figure 1b presents two pictures of the rocket exhaust gases taken at the moment of ignition and at about 1.5 s firing time.

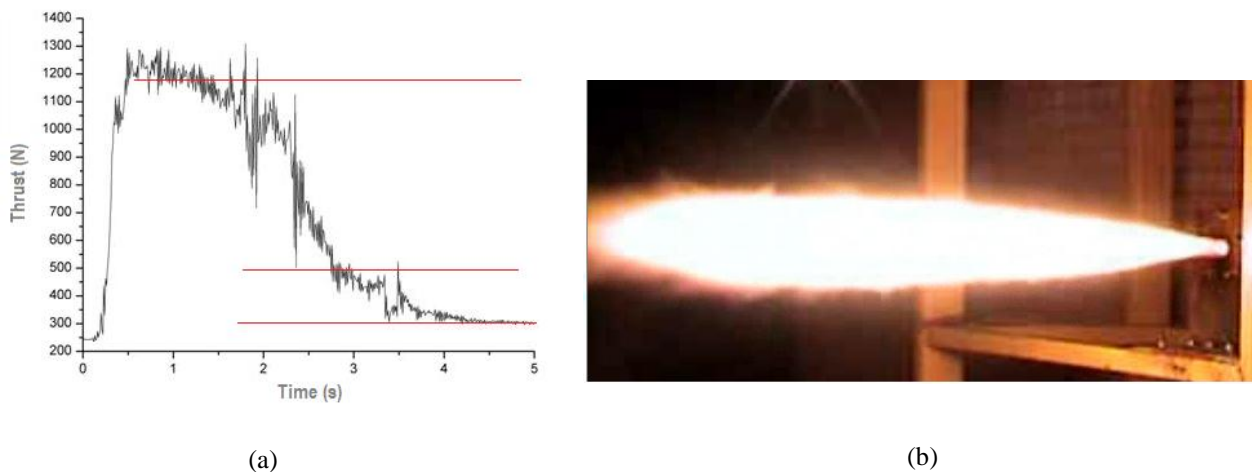


Figure 1. Thrust curve for a 1500 N hybrid motor (a) and picture taking during the firing test (b).

As it can be seen, designed thrust was not obtained but the atomization process, through pressure swirl atomizers, allowed stable operation at very high oxidizer mass flux. We could not get stable operation with another injection plate (showerhead style) with a series of holes giving similar oxidizer mass flux. Therefore, it can be inferred a possible influence of the oxidizer injection performance and type on the stability of the combustion process. From Fig. 1(a) it can be noticed two levels of thrust, one near 1200 N and the second at about 500 N. This second level is due to lower oxidizer flux when the oxidizer tank was filled only with gaseous nitrous oxide. This shows the ability of the system in operating with variable oxidizer mass flux, while providing stable thrust.

From our research activities, Bertoldi (2005) reported a series of firing using a small hybrid rocket (paraffin based) with just one injector (pressure swirl atomizer) for the nitrous oxide. The following equation for the average regression rate was suggested

$$\bar{r} = 0.72 \bar{G}_{ox}^{0.67} \tag{2}$$

In (2), regression rate is in mm/sec and oxidizer mass flux is g/cm²/sec. This correlation gives regression rates much higher than (1) as proposed in Karabeyoglu et al. (2004).

Nitrous oxide and liquefying fuels have been the preferred propellants of our propulsion research activities in hybrid rocket systems. Nitrous oxide is a non toxic, long term storable, has good density, a high vapor pressure and has good overall performance, as pointed by Thicksten et al. (2008) in a paper dedicated on how to handle such oxidizer in hybrid rocket motor testing. Nitrous oxide has also self-pressurizing characteristics. More recently we focused on two main subjects: finding alternative fuels which can be classified as liquefying solids as well as understanding how this type of fuel responds to trolling. The following sections present the test bench and the results of this research.

3. EXPERIMENTAL SETUP AND PROCEDURE

A schematic drawing of the experimental setup is shown in Fig. 3. Basically, the facility consists of a nitrous oxide delivery system, for both ignition and firing of the motor, liquefied petroleum gas (LPG) for ignition and N₂ for flame extinction. An electronic system, for thrust and pressure data acquisition as well as a controller for the oxidizer mass flux completes the apparatus. The oxidizer, for firing, can be delivered as gaseous jet-swirl atomizer not installed) or liquid, depending on the proposed test. Oxidation of LPG, for the motor ignition, was always realized with gaseous nitro oxide. The firing line of oxidizer has a control valve (electro-pneumatic), flanged, with a shut-off valve mounted at the entrance and a check valve mounted at the exit. The gas fuel ignition line (LPG) is comprised of a small LPG tank (100 g) a solenoid valve and two check valves, for redundancy, to avoid firing nitrous oxide, at much higher pressure, to mixture with hydrocarbon gases. The ignition system operates with excess of oxidizer, to facilitate the combustion of paraffin gases after thermal decomposition of the nitrous oxide. In a cross connector (1/2") a spark plug is mounted opposite to the LPG connecting line. The gaseous oxidizer line is connected to the third port of the cross flowing towards the flange of the motor. The cross operates as a small combustion chamber for the LPG and the gaseous oxidizer.

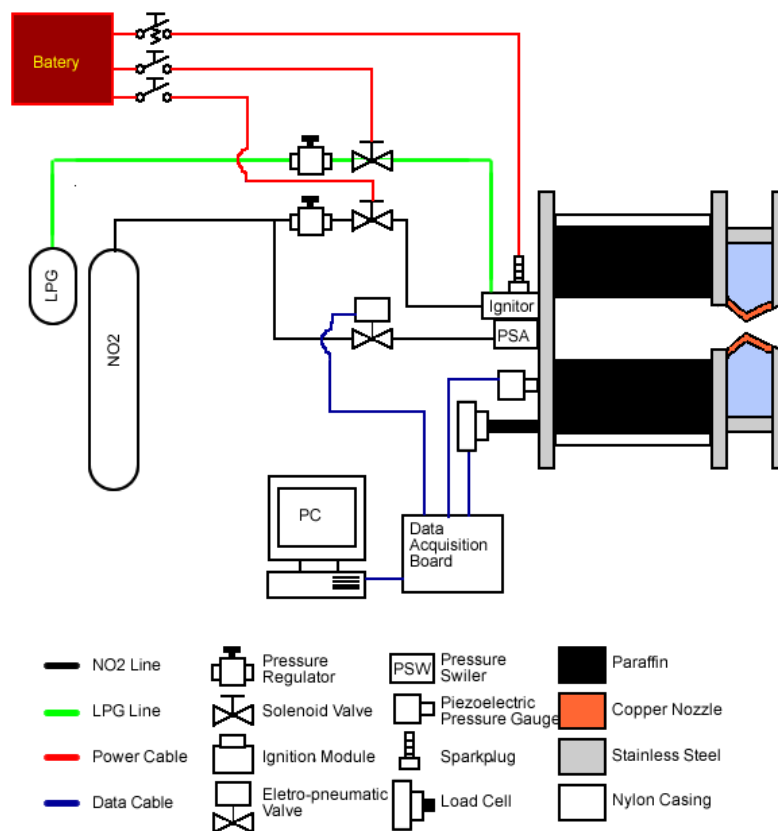


Figure 2. Test bench schematics.

The hybrid motor for the static tests can be seen in Fig. 3. This motor was designed to sustain firings up to 40 s. The motor has no pre and post combustion chambers. The grain internal port is, therefore, the only volume available for the

combustion to take place, before the expansion process. Long time firings would affect nozzle integrity. We, therefore, proposed a cooling system for the nozzle which was fabricated from copper S45 alloy. Water is allowed to pass through the nozzle outside surface for cooling purposes. This cooling system allows firing times as long as 40 s when the external diameter of the solid fuel is large enough. The motor is made of a 185 mm external diameter cylinder, 220 mm length, machined from high density polyethylene. The solid fuel grains are prepared directly into the polyethylene casings, after resting them vertically (longitudinal axis) to allow filling with liquid paraffin. The desired internal port was obtained by rotating the casing longitudinally. We have four of those casings, making the whole process of fabricating the grains very straightforward, allowing a good deal of firings tests in short periods of time.

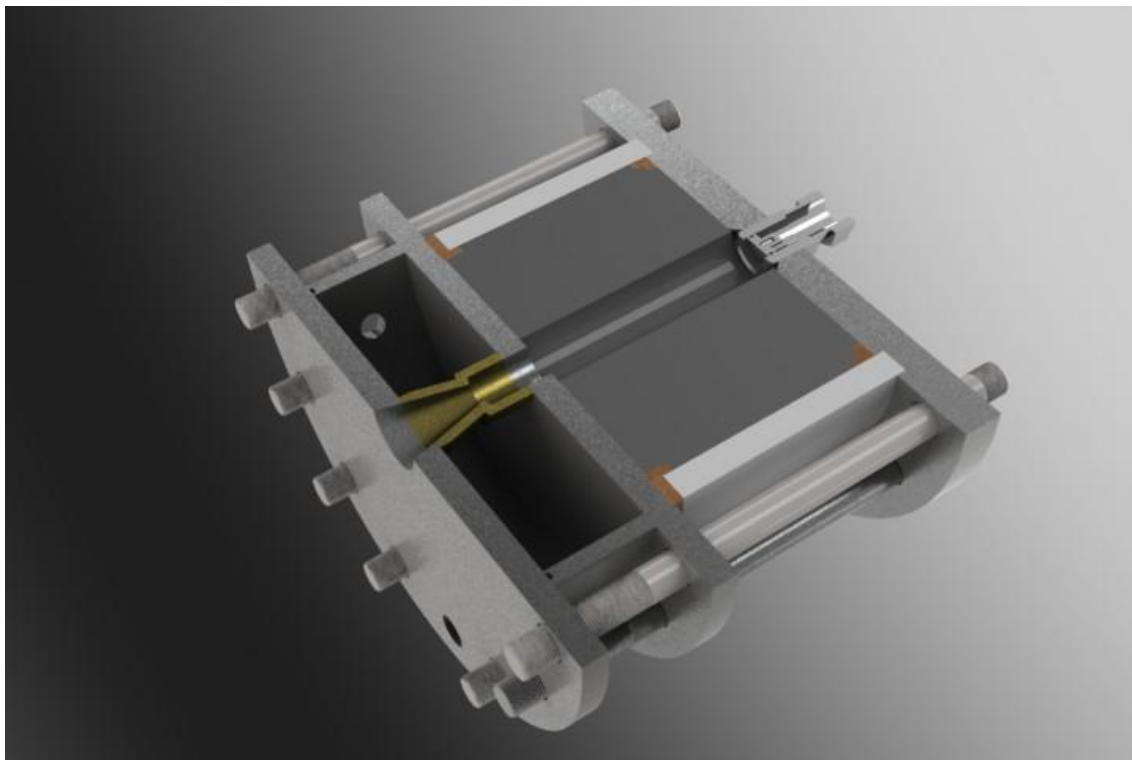


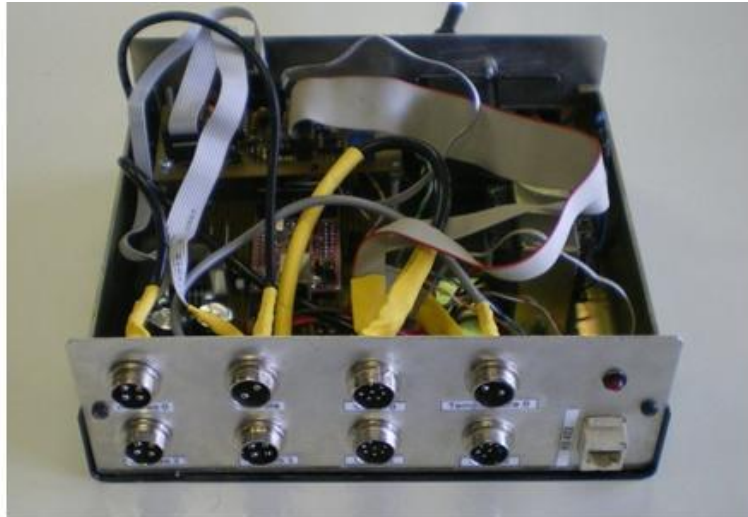
Figure 3. A cutoff view of the static hybrid motor.

When operating with liquid N_2O a jet-swirl atomizer is mounted at the aft end of the motor at the center of the main flange. This device is inserted into the SAE 304 steel connector (nipple) as shown in Fig. 4. By such means, the atomizer can be easily substituted. A code developed on EES platform was used to design the injector for the desired performance. In this work, however only gaseous N_2O was used, for safety reasons. It is easier to adjust the pressure when the oxidizer is in gaseous phase, as opposed to liquid phase. Future work will be carried out using the preferred injection system (jet-swirl atomizer). This type of operation was, therefore, not possible on account of the high saturated pressure of nitrous oxide at room temperature (55 atm) as compared to the maximum allowed pressure of the control valve (30 atm).

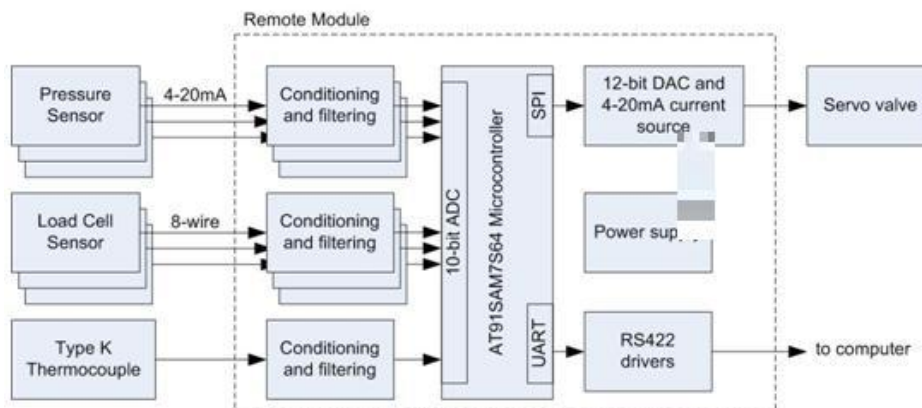
The electronic acquisition system and control has being designed specifically for data reading as well as thrust modulation and control. A photo of the system (a) and its internal diagram (b) are shown in Fig 4. The unit is comprised of a microcontroller-based data acquisition system for pressure transducers (3), load cells (3) and one type K thermocouple inputs. Specific signal conditioning and filtering circuits prevents from aliasing and delivers continuous voltages to a 10-bit analog-to-digital (ADC) converter. This device is part of an AT91SAM7S64 32-bit, 60MHz microcontroller. The servo-valve is commanded by a 4-20mA link. The system communicates to a microcomputer using an RS-422 full-duplex, differential serial link at 115200 bps. Since RS-422 has been chosen as physical communication standard, a cable connecting the data acquisition system and the microcomputer can be up to 100 m length, for safety when testing real motors. The microcontroller sampling rate for pressure transducers works at 300 Hz, and for the other sensors at 100 Hz. The prescribed sampling rate for pressure can be increased accordingly for studies on combustion instabilities in hybrid rocket engines, which are typically of low frequencies. All data sampled receives a timestamp and is pushed to a circular queue. In the future, the embedded microcontroller will be used also to control the hybrid motor thrust.

An interface code was written to help users acquire data as well as to operate the oxidizer control valve from a microcomputer. This user interface program requests the queued data periodically through serial link and specific

protocols from the data acquisition board. The program saves collected data in a set of MATLAB.mat files. A user may also set a prescribed flux of oxidizer against time through a prior-to-fire written script. This is made via Lua programming language. This has been achieved by incorporating to the code an open source Lua script interpreter (<http://www.lua.org/>). The code was designed to operate, in the near future, as a control system for thrust modulation of a flying hybrid rocket motor.



(a) Data acquisition and control system.



(b) Block diagram

Figure 4. Data acquisition system and control.

To evaluate the procedures and check the acquisition system and control, a couple of static hybrid motor firings were carried out and one of the results is shown in Fig. 5. The desired position of the control valve during firing is set previously following a script written in an appropriate file. The script is executed after 3 s of fuel burning at lower oxidizer injection rate (ignition phase). The pressure curve on Fig.5 shows two ignition attempts, in which the first failed. An important characteristic of hybrid motor has to do with its transient operation, as the melting area of the combustion port increases. For a constant oxidizer mass flux, that would alter the OF ratio, thus altering the specific impulse. In any case, one can see a rather stable operation after about 4 seconds the ignition of the motor. The script for this firing was written in order to give steady operation of the motor for 10 seconds.

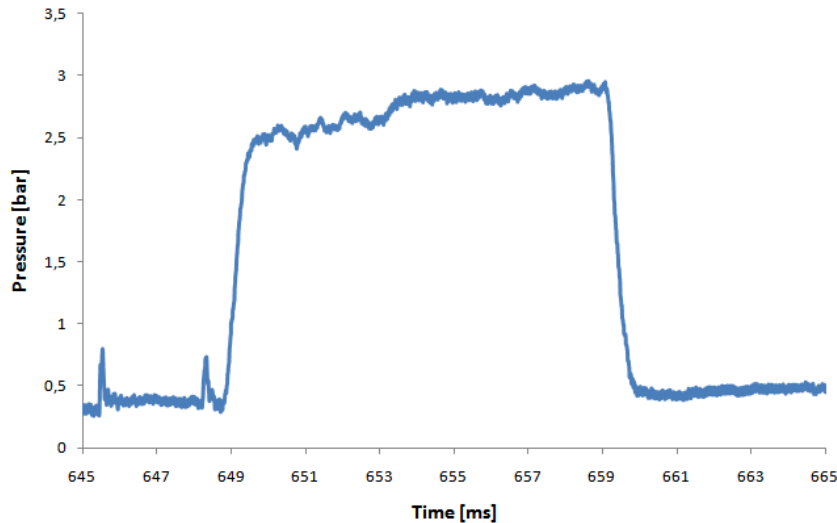


Figure 5. Chamber pressure against time, static firing.

4. RESULTS AND DISCUSSION

Figure 6 presents a thrust against time for the hybrid motor operating on solid paraffin and nitrous oxide. The high amplitude oscillation of the thrust is, possibly, due to the lower ullage volume and the coupling between the oxidizer tank and the combustion chamber. Nonetheless, the figure shows, partially, the response of the thrust to the variation of the oxidizer mass flux. After ignition (a smaller peak before 290 s) the rise on thrust can be seen. It is important to mention that the control valve is operated by a pneumatic piston filled by another small auxiliary pneumatic valve. The response of the system is expected to be slow, as compared to a liquid injection system. After 100% oxidizer injection, from 290 to about 298 s, the valve shifted to 80% mass flux for 5 s time period. The engine thrust increased when the valve was fully open, then, stabilized for a couple of seconds (80% set point). When the valve further decreased the oxidizer flux to about 40% the thrust decreased to around 80 N. Due to compressibility effects, the engine thrust decreased slowly and tried to stay at that level but the script initiated the shutting down process. This behavior was replicated in some other tests. Hybrid rockets, tough, operate with liquid injection. At this point, the jet-swirl atomizer should be qualified before attempts to have variable thrust in our rocket motor. We, therefore, decided to check thrust modulation by “on” and “off” oxidizer injection cycles.

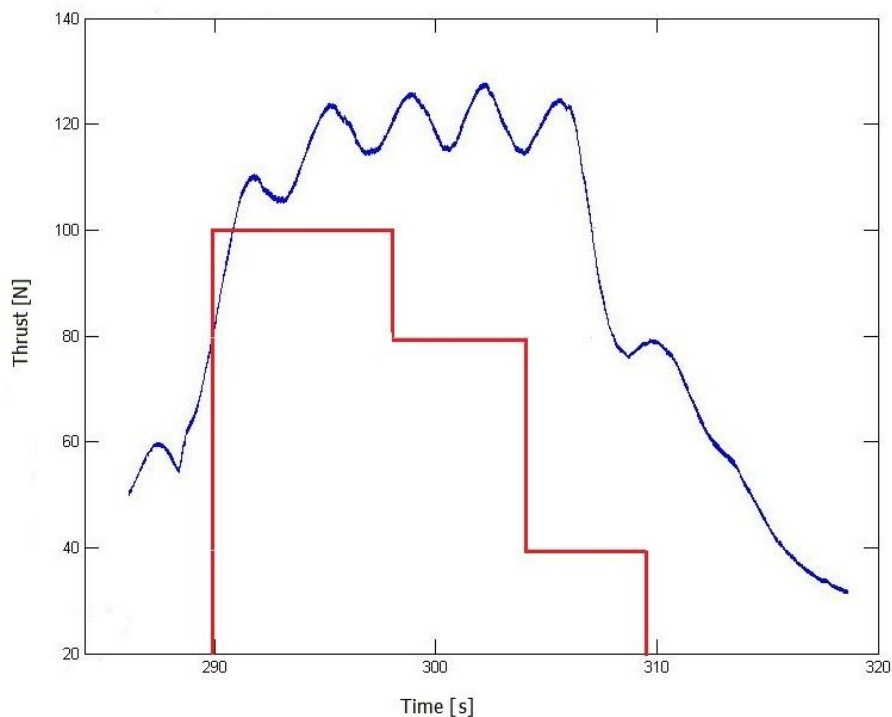


Figure 6. Thrust modulation during firing.

Figure 7 shows one firing test in which the valve shuts down, 15 s after ignition. The upper curve in figure is related to the prescribed level (a script written in a file) of gaseous oxidizer flux, through the position of the valve actuator, in terms of percentage, from totally closed (0%) to fully open (100%) along firing time. The bottom curve shows combustion chamber pressure against time, following the position of the actuator of the valve. The prescribed script, set prior to the test, was such that the valve would be fully open in about 3.5 seconds, remaining at 100% load for 4 seconds, and then closing in a decay ramp to 0% in ten seconds time span. The valve then stays shut for about three seconds, resuming the previous profile afterwards, and then the firing was interrupted at 28 seconds. By such means, some desire impulse could be obtained without any control system complexity, just operating the motor through “on” and “off” cycles. Care must be taken as to avoid long “off” mode that could put at risk the combustion chamber re-ignition. This test proved the re-ignition capability of a hybrid motor in the absence of any auxiliary means (heat source). The pressure curve did not follow, strictly, the valve actuating profile. The test was conducted with gaseous oxidizer, which provided some dumping effect on chamber pressure. So, the oxidizer flux was actually altered by the valve under and above the 30% line. Above that the flow is choked in the valve internal geometry, thus offsetting the modulation.

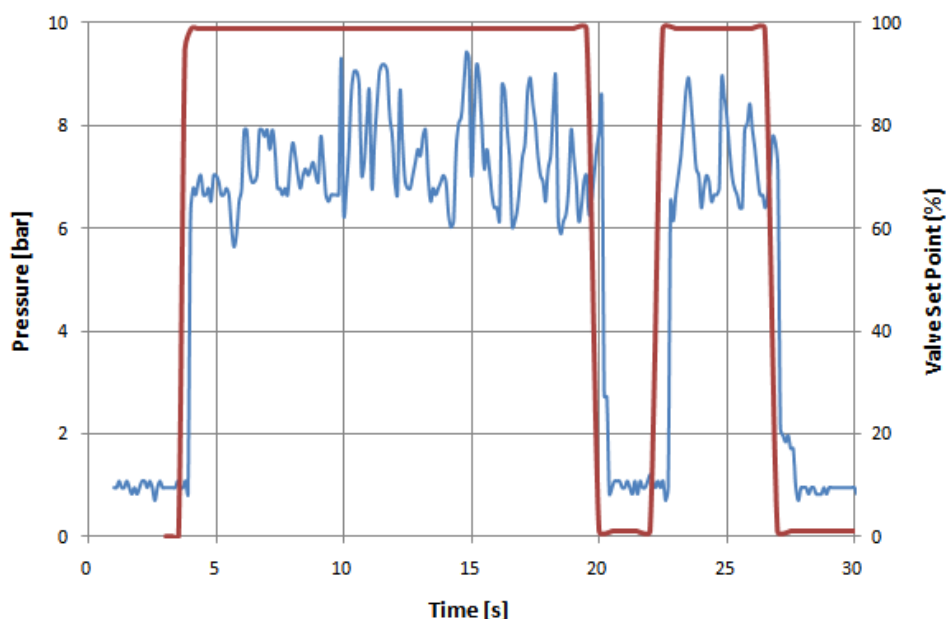


Figure 7. Thrust modulation via on-off cycle.

5. CONCLUSION

A test bench was proposed to carry out studies in hybrid rocket thrust modulation. The propellants of the engine were liquefied fuels, such as paraffin and special waxes, and nitrous oxide. An electronic system was proposed and built to adjust a pneumatic globe valve actuator to control the flux of oxidizer to the combustion chamber. By such means, it was shown that thrust modulation was possible in hybrid rocket motors. Two approaches were tested. One in which the flux is altered to a desired set point and the other by means of shutting down and re-ignition cycles.

6. ACKNOWLEDGMENT

We are thankful to the Brazilian Space Agency for supporting this work under the Uniespaço program (2007).

7. REFERENCES

- Almeida, L., A., R., Santos, L., M. C., (2005) “Projeto, Construção e Lançamento de um Foguete Híbrido a Base do Par Propelente Parafina- N_2O ” – projeto de graduação, Universidade de Brasília, 83p.
- Bertoldi, A. E. D. , “Experimental investigation of the combustion behavior of paraffin and nitrous oxide in hybrid rocket engines”, Master Dissertation – in portuguese, University of Brasília, 2007.

- Cacalleri, R.J., and Loehr, R. D. , “Hybrid rocket propulsion performance prediction”, AIAA paper 2005-3548, 41st AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, Tucson, Arizona, 2005.
- Casalino, L. and Pastrone, D., “Optimal design and control of hybrid rockets for access to space, AIAA paper 2005-3547, 41st AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, Tucson, AR, USA, 2005.
- Karabeyoglu, A., “Hybrid propulsion for future space launch”, 50th Anniversary Symposium and Celebration, University of Sanford Aero/Astro Symposium, 2008.
- Karabeyoglu, A., Zilliac, G., Cantwell, B. J., Zilwa, S. De, and Castelluci, P., “Scale-up tests of high regression rate liquefying rocket fuels”, Journal of propulsion and Power Vol. 20, No 6, 2004.
- Knuth, W. H. , Chiaverim, M. J. , Grame, D. J., and Sauer, J. A. , “Solid fuel regression rate and combustion behaviour of vortex hybrid rocket engines, AIAA 99-2318, 1999.
- Oiknine, C., New perspectives for hybrid propulsion, AIAA paper 2006-4674, 42nd AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, Sacramento, California, 2006.
- Rajesh, K. K. , “Thrust modulation in a nitrous-oxide/hydroxyl-terminated polybutadiene hybrid rocket motor”, AIAA paper 2006-4503, 42nd AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, Sacramento, California, 2006 .
- Santos, L., M., C., Almeida, L., A., R., Fraga, A., M., Veras, C., A., G. (2004)“Experimental Investigation of a Paraffin Based Hybrid Rocket”. In: 10TH Brazilian Congress of Thermal Sciences and Engineering, Rio de Janeiro.
- Thicksten, Z.,and Macklin F., John Campbell, Handling considerations of nitrous oxide in hybrid rocket motor testing” AIAA 2008-4830 44th Joint propulsion conference, 2008.
- Viegas, F.L., Salemi, L.C., . Projeto e Construção de uma Bancada de Testes Estáticos de Propulsores e de um Propulsor Híbrido. 2000, Trabalho de Conclusão de Curso. (Graduação em Engenharia Mecânica) - Universidade de Brasília.
- Waidmann, W., “Thrust modulation in hybrid rocket engines”, Journal of Propulsion, vol. 4, No 5, 1988, pp 421-427.