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DESIGN OF A HOVERING SOUNDING ROCKET STAGE FOR MEASUREMENTS IN THE HIGH ATMOSPHERE

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ABSTRACT:

In order to perform specific measurements in the high atmosphere region, the High Atmosphere Soarer (HAS) sounding rocket upper stage is under development at the German Aerospace Center and Bayern-Chemie. This paper briefly describes the scientific mission behind as well as the HAS vehicle concept. More emphasis is dedicated to the description of the trajectory, the technology of the controllable gelled propellant rocket motor and the design of the remaining key propulsion system components.

1. INTRODUCTION

Due to the predominately low ambient air density and pressure conditions, in-situ measurements in high atmosphere regions (e.g. mesosphere) are only possible by means of sounding rockets. However, the typical trajectory of a sounding rocket is of a suborbital, elliptical and relatively steep nature, practically providing only several seconds during ascend as well as descend to perform the desired measurements. In order to improve the scientific gain and provide essentially longer experiment times as well as spatial expansion in the relevant altitude levels, the German Aerospace Center (DLR) and Bayern-Chemie GmbH are working on a thrust controllable, "hovering" upper stage for sounding rocket applications, called the High Atmosphere Soarer (HAS).

Besides the above described atmospheric physics-based application, the technology can also be utilized for hypersonic flying testbed investigations and from a general perspective also for return and landing vehicles such as return to earth booster stages as well as planetary landers.

2. HAS VEHICLE CONCEPT

The projected vehicle mainly consists of a conventional first stage solid propellant booster motor, a yo-yo de-spin & separation unit and the HAS upper stage with an ejectable nose cone structure, see figure 1.

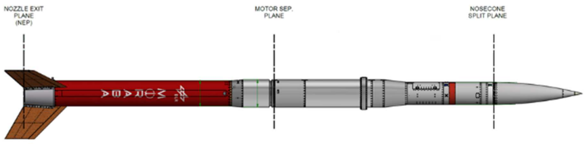

Figure 1. Complete HAS vehicle with Improved Malemute booster motor.

Figure 2 shows a section cut of the HAS upper stage vehicle including the thrust controllable engine with its gimbal support for thrust vector control, the two-phase tank system, the high-pressure system for feeding the propellant and providing the cold gas system (CGS) for attitude control. The payload partly comprises the typical support systems for payload recovery, the service module including the onboard flight computer, the telemetry system, the power supply unit as well as the guidance and navigation system.

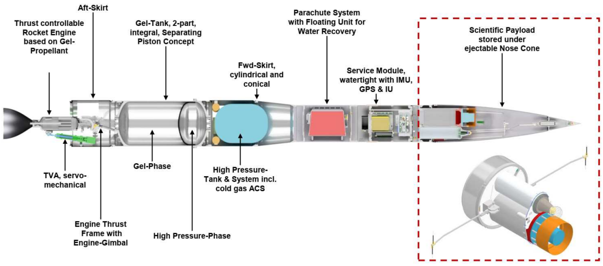

Figure 2. HAS upper stage vehicle with propulsion and payload section.

The scientific part of the payload is located at the front of the vehicle and is protected by the ejectable nose cone structure during the ascent through the denser atmosphere layers. Thereby the scientific instrumentation can consist of Langmuir and ion probes as well as particle collectors.

3. TRAJECTORY

The flight of conventional, unguided sounding rockets consists of a high-acceleration atmospheric flight phase, a coasting atmospheric flight phase, and upon leaving the dense parts of the atmosphere a purely ballistic flight path. Due to the inherent imprecision in predicting the exact vehicle performance and environment characteristics and perturbations, the actual trajectory is subject to dispersions [1, 2, 3]. For the study of medium and upper atmosphere layers with the vehicle traversing the altitude layer of interest, the (nominal) target apogee needs to be set above the target altitude layer, considering that the vehicle will reach the target altitude even in the presence of perturbations acting to lower the actual apogee. However, increasing the apogee actually increases the vertical velocity with which the vehicle traverses the target altitude layer, and hence shortens the time it may spend therein. The higher the uncertainties pertaining to the dispersion distribution, the higher the delta of target altitude to target apogee, and hence the shorter the duration in the target altitude band. There are few options available for reducing the dispersion of single stage unguided vehicles.

A throttleable second stage, however, is able to eliminate the dispersion as well as to enable completely new mission profiles due to its unique maneuvering capabilities. The mission design for the HAS vehicle envisages an apogee after first stage burnout as close as possible to the target altitude (although the performance penalty for "undershooting" the target altitude is less severe than for "overshooting") followed by a continuous burn and maneuvering phase for the upper stage.

For such a two-stage vehicle, the trajectory on the up-leg consists of the following phases:

1. High-acceleration, unguided first stage burn.
2. Atmospheric coast phase.
3. De-spin, nosecone and stage separation.
4. Maneuvering (CGS) prior to HAS upper stage ignition.
5. HAS upper stage burn phase with maneuvering (CGS + TVA).
6. HAS upper stage shutdown and maneuvering (CGS).

Unguided fin-stabilized vehicles may use canted fins to introduce a spinning motion about the longitudinal axis ("rolling") which reduces the magnitude of dispersion. This rolling motion needs to be eliminated prior to upper stage operation, which is partly achieved by a yo-yo de-spin system. Due to the operational principle of the de-spin system, it can only be activated successfully once the atmospheric influence has sufficiently subsided as to not impede on the yo-yo unravelling; for the current vehicle configuration, this is achieved at approximately 50 km altitude.

The experiment phase (e.g. atmospheric sampling) shall be within an altitude band of 80-90 km, however, it may commence at any point after HAS stage separation and nose cone ejection. During the gel motor burn potential disturbing effects on the scientific results such as plume impingement and induced vibrations need to be further investigated during the development of the HAS.

For the upper stage engine operation, several concepts may be identified, each with unique advantages and disadvantages:

1. Maintain a vertical orientation throughout the entire burn phase: No change in horizontal velocity, maximum possible hovering time due to low required thrust.
2. If the apogee at stage separation is below the target altitude, fire vertically.

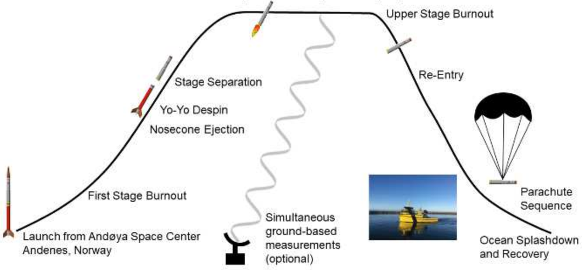

Figure 3. HAS exemplary concept of operation.

Once the vehicle has passed the lower threshold of the target altitude band, the experiments conclude and the recovery phase begins. The vehicle starts the safing process by aligning itself for a flat spin reentry and, in case of a premature mission abort, dumping residual propellant. The remaining RCS capacity is used to start a rolling motion to distribute the impact of reentry heating. At an altitude of ~5000 m a two-stage parachute system is activated, and the vehicle splashes down softly in the Arctic ocean. While floating in the sea the payload is recovered by the recovery vessel, allowing the examination and partly reuse of the experiments and the flight hardware.

4. MAIN DESIGN FEATURES

The following sub paragraphs describe the main design features of the HAS upper stage propulsion system.

4.1. Gel Propellant Rocket Technology

The thrust-controllable gelled propellant rocket motor (GRM) technology is under development by a joint program of BC, DLR and FhG-ICT that started in 2001 with funding of the German MoD. The specific technical aspects, the progress and achievements are reported in references [4, 5, 6] and the literature cited therein. Hence, in this place we just outline the specifics of the motor for the HAS and the piece of information about GRM technology that is needed for the understanding of this paper.

The principle of operation of a GRM is similar to that of a liquid rocket motor (LRM). Propellant tank and combustion chamber are separated. This allows to control the propellant mass flow from tank to rocket motor, and in consequence the control of thrust level.

The gelled rocket propellant (GRP) in the tank behaves roughly like a solid. For the application with the HAS key advantages are the absence of sloshing in the tank, the excellent controllability and combustion stability, the insensitivity and the environmental friendliness of the propellant. The high degree of safety is also a result of the fact that three independent functions need to operate correctly in order to start the operation of the GRM:

- Pressurization of the GRP tank
- Ignition of the igniter
- Opening of the GRP valve and start of the propellant flow

High-pressure gas feeds the gelled propellant through a control valve into the injector of the GRM. Upon passing of the injector channels, the gel structure of the propellant is destroyed and the propellant is sprayed like a liquid into the combustion chamber. The monopropellant decomposes and produces the hot gas that is ejected through the nozzle with a fixed throat cross-section area. The thrust control in the required limits from 2-6.5 kN can be done by variation of the combustion pressure alone. Variable injector elements or a nozzle with variable throat cross-section area [7] are not necessary in this case.

Early ideas on the propulsion system of a hovering stage using a GRM are described in [8]. The design of the GRM of the HAS stage uses proven materials and methods. The load-carrying structures and the injector are made of steel. The internal heat shield of the un-cooled combustion chamber is made of BC-proprietary ablative material Silfen. For the nozzle throat the molybdenum alloy TZM® or Ceramic Matrix Composite (CMC) material can be used. Materials and design methods have been verified by a project that demonstrated a continuously operating DACS technology demonstrator for an operation time of one minute.

The gelled rocket motor propellant GRP 063 is a formulation that produces particle-free gas to limit the pollution of the mesosphere. BC has a continuously operating production facility that can produce up to 300 kg/hour of this propellant. In view of the moderate combustion temperature of 2000 K the propellant shows a good specific impulse of about 2500 m/s at operation in near vacuum ambient pressure.

Because the gelled propellant is much harder to ignite than the basic propellant blend in liquid state, a powerful igniter is needed. It consists of solid propellant grains that are integrated in the combustion chamber and produce a pressure of about 2-3 MPa for a time of up to 0.5 seconds.

The pressurization of the GRP tank is ideally done before the ignition of the first stage motor. The pressurization of the tank adds mechanical stability, particularly against bulging, and the launch can be stopped if the pressurization should fail.

4.2. Gel Propellant Tank

The gel propellant tank is designed [9] for three main purposes at which the first one is to store the propellant during the flight. Its internal fuel volume is resulting in a mass of around 100 kg for the specific gel propellant.

The second purpose of the tank is to feed the propellant to the engine. Thus, the tank is part of the propellant feed system utilizing a piston to push out the propellant towards the engine. The piston is driven by high pressured gas and can move throughout the whole length of the tank in order to feed all available propellant, see figure 4.

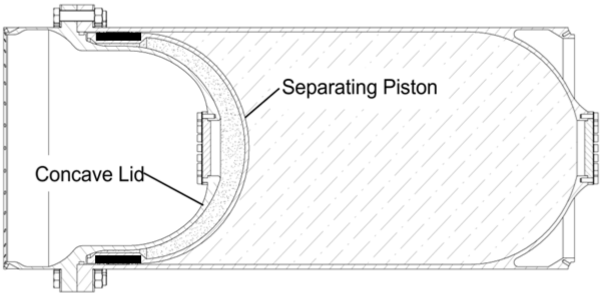

Figure 4. HAS upper stage gel tank with concave lid.

The tank's third purpose is to form a part of the rocket's structure. It is designed to be an integral part of the rocket connected to other modules via radial-axial (RADAX) flanges on top and on its bottom. The tank is made from an aluminium alloy and is designed in three pieces: The cylindrical part, which includes the lower dome, the piston which is placed inside the tank and the top dome. The top dome and the cylindrical part are connected via a flange. Although being a significant contributor to the tank's mass, the flange is needed to insert the piston and to check the inside for potential flaws or to perform maintenance in the current prototype stadium.

Since the tank is part of the rocket structure, it also needs to be able to withstand all adjacent forces and flight loads besides the internal pressure. The high-pressure gas is introduced in the top part of the tank, filling the ullage above the piston and pushing it downwards. Thereby the piston is sealed to prevent leaking of propellant or gas using a special dynamic piston sealing. In order to keep ullage as low as possible and to provide as much space as possible for valves and further gear upwards the tank, the top dome is designed as an inward pointing (concave) shell. This design still ensures good behaviour concerning additional bending moments in the flange as well as the cylindrical section. It significantly reduces the ullage as well as needed gas volume compared to an outward pointing dome (convex) and provides an essential reduction of total building volume and mass, see figure 5.

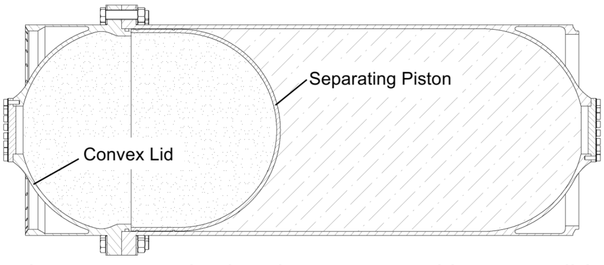

Figure 5. Standard tank geometry with convex lid.

4.3. Gel Propellant Flow Control System

The thrust of a GRM is controlled by the control of the GRP mass flow. For a GRM having nozzle and injector with fixed geometry, the pressure in the combustion chamber (CC) is roughly proportional to the GRP mass flow. Boundaries to be respected are the upper limit of CC pressure, given by the mechanical stability of the CC structure, and the lower limit of combustion pressure determined by the combustion properties of the GRP. Because ambient pressure at mesosphere altitude is very low, the thrust of the GRM is roughly proportional to the CC pressure.

In principle, propellant flow could be controlled by varying the pressure in the GRP tank. This method is readily dismissed because the rate of pressure change in the big GRP-tank is very slow, and turning down the GRM thrust would mean to rapidly vent a large mass of gas, i.e. a significant waste of gas and structural mass for the gas tanks.

Hence, the method chosen is to de-couple the GRP mass flow and the GRP tank pressure. The GRP tank pressure is kept at a constant value by a pressure reducer till the gas pressure between the high-pressure gas storage tanks and the GRP tank has equalized. The GRP mass flow is controlled by a valve between the GRP tank and the GRM. The demand on thrust level determined by the guidance, navigation and control unit is transferred into a control signal to the actuator of the GRP valve. The measured CC pressure is used to feed back the state of GRM operation and to prevent over- and under-pressure in the CC. Because the CC pressure is roughly proportional to the GRP mass flow, the CC pressure signal can be integrated over time to estimate the propellant consumption.

Because GRP is a non-Newtonian fluid, the correlation between open valve cross-section, pressure and GRP mass flow is non-linear.

4.4. High Pressure Gas Tank and Gel Tank Pressurization System

The high-pressure gas control system is required to ensure the full functionality of the HAS thrust controllable upper stage, which has two primary tasks. On one hand, it ensures that the gel-based propellant is pressed or fed from the gel tank to the combustion chamber by pressurizing the gel tank with nitrogen. The second task is to supply the cold gas system (CGS) with nitrogen in order to ensure the functionality of the CGS and thus enabling the attitude control of the gel-based upper stage during hover flight.

In addition to the two primary functions, the system has various secondary functions such as manual and remotely controlled venting via a needle valve and the cold gas nozzles for attitude control of the HAS. Furthermore, the system is pressurized remotely via a servo-controlled piston valve, hereby the gel tank can be pressurized separately.

Two burst discs are installed to protect the gel tank from overpressure. Figure 6 shows a longitudinal cut of the high-pressure system and the CGS of the HAS.

The systems maximum operating pressure is derived from the specifications of the high-pressure gaseous nitrogen reservoir. For the two primary tasks, the pressure inside the system is reduced by spring-loaded pressure regulators. For gel propellant transport, the pressure is reduced to the maximum operating pressure of the gel tank. For the supply of the cold gas system the pressure is further reduced. The different system pressures are monitored by pressure sensors.

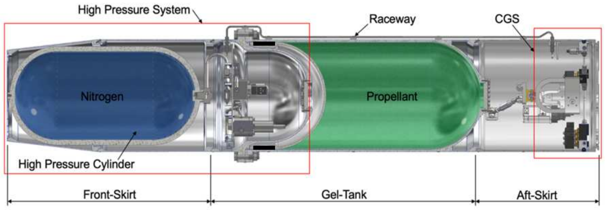

Figure 6. HAS high-pressure system and CGS.

The high-pressure gas reservoir is a commercial of the shelf liquid gas tank consisting of a carbon fibre reinforced plastic / glass fibre reinforced plastic (CFRP/GFRP) mixture and an inner liner made of thermoplastics. In addition to the high-pressure gas reservoir, various system components such as valves, sensors, fittings and tubes are installed inside the system and are more detailed described in reference [10].

4.5. Attitude Control System

In order to realize the envisaged non-ballistic flight path of the HAS upper stage, the vehicle needs to be equipped with a respective attitude control system consisting of a cold gas unit for unpowered and of an additional thrust vector assembly (TVA) for the powered flight regimes.

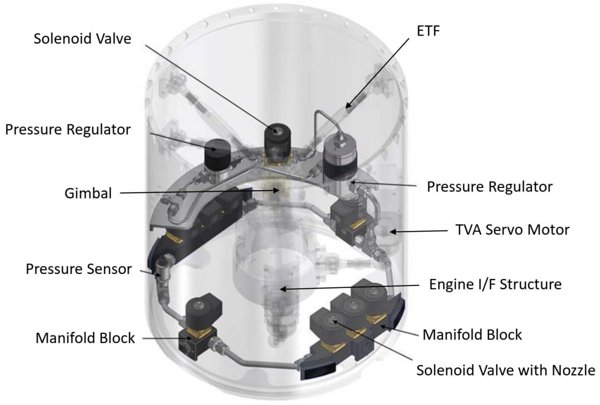

Figure 7. HAS CGS, TVA and ETF.

Both systems are mostly housed inside the aft-skirt module below the gel tank structure, see figure 7.

Due to inherent thrust vector misalignments of the upper stage engine and the relatively low reaction forces of the cold gas system a TVA is needed in addition to the cold gas system for all lateral motions during the powered flight regime, while the roll motion is controlled by the roll nozzles of the CGS. For ensuring the TVA motion the throttleable engine needs to be supported via a gimbal joint between the engines upper burning chamber structure and the engine thrust frame (ETF).

All unpowered flight regimes, mainly during upper stage coasting after stage separation and after upper stage engine shutdown, shall be purely controlled by the CGS around all three axes. As described in the high-pressure system section the CGS is supplied by gaseous nitrogen.

5. OUTLOOK

The herein presented work is part of an ongoing development planned to be finished by end of 2023. Its major milestones will be a ground-based hover test as proof of concept planned for the end of 2022. A first test flight together with relevant scientific payload instruments is planned in mid 2023.

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