HEMP Thruster Assembly Performance with increased Gas Tubing Lengths of Flow Control Unit

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Abstract: The Business Unit Electron Devices of Thales Deutschland has developed and qualified a novel electric propulsion system for station keeping of OHB's SmallGEO satellite platform. In order to cope with the increased interface temperature range of electric orbit raising applications as well, Thales is further developing the HEMP Thruster Technology to satisfy also this customer need. When the Thruster Module is mounted at the tip of a thruster orientation mechanism, the HEMP Flow Control Unit has to be separated from the Module and placed to a temperature controlled area of the spacecraft at distance from thruster and neutraliser. Consequently, the controller has to cope with several meters long tubing. This longer tubing increases dead time of the closed loop system. Thales has performed several activities in order to establish know how on the effects of long tubing on the performance of the propulsion subsystem.

Nomenclature

ESPSS	=	European Space Propulsion System Simulation
FCV	=	Flow Control Valve
FCU	=	Flow Control Unit
FR	=	Flow Restrictor
HEMPT	=	High Efficiency Multistage Plasma Thruster
HTA	=	HEMP Thruster Assembly
HTM	=	HEMP Thruster Module
PSCU	=	Power Supply and Control Unit
TRL	=	technology readiness level

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I. Introduction

THE HEMP-Thruster technology is reaching maturity through the qualification within the HEMP-TIS project, funded by the DLR. The inauguration flight of the HEMP Thruster Assembly (HTA) is intended on the German Heinrich Hertz (H2Sat) mission. The HTA 3050 consists of the key components: High Efficiency Multistage Plasma Thruster (HEMPT) 3050, Hollow Cathode Neutralizer HCN 5000, Flow Control Unit (FCU) and Power Supply and Control Unit (PSCU). Thruster, Neutralizer and FCU are mounted from both sides onto one common baseplate forming the thruster module. On the one hand, this compact design allows easy testing, handling and installation onto the spacecraft. On the other hand, the module has to be kept within a temperature range compatible to all mounted components. Since valves of the FCU are typically temperature limited components, which are actively dissipating heat, these components are limiting the temperature range of the whole module.

In the last years, satellite integrator needs evolved more and more towards usage of all-electric propulsion requiring higher thrust compared to station-keeping application. On satellite level, it can be beneficial to consider the usage of the electric orbit raising thrusters also for station keeping. The hereby required orientations of the thrust vectors are different between orbit raising and station keeping application. To this end, electric propulsion subsystems for orbit raising and station keeping include a thruster orientation mechanism pointing the thrust vector to the required position. Mounted at the top of the mechanism’s arm, thrusters shall be capable of operation with nearly no conductive heat transfer to the spacecraft radiators at all.

In order to cope with the increased interface temperature range, the HEMP FCU has to be mounted to a temperature controlled area of the spacecraft at a distance from thruster and neutraliser. Consequently, the controller has to cope with several meters long tubing. This longer tubing increases dead time of the closed loop system and influences start-up and loop stability performance of the propulsion system.

This paper presents the functional architecture and the performance of the beam current control loop of the HTA 3050 in Chapter II. Chapter III is dedicated to the results of the fundamental tests performed in order to determine propagation velocity of pressure waves in 1/8” tubing. The results are included in the established 1-D simulation of the HTA 3050 which are predicted in Chapter IV. Finally in Chapter V, the results are summarized and the conclusion is presented.

II. HTA beam current controller

In line with the straight forward but reliable design concept of the HTA, the FCU does not include a pressure sensor in order to reduce complexity.[1] Instead, anode current of the thruster is directly used as feedback signal. Measurement of the anode current is provided by the anode current measurement unit of the PSCU as shown in figure 1.[2]

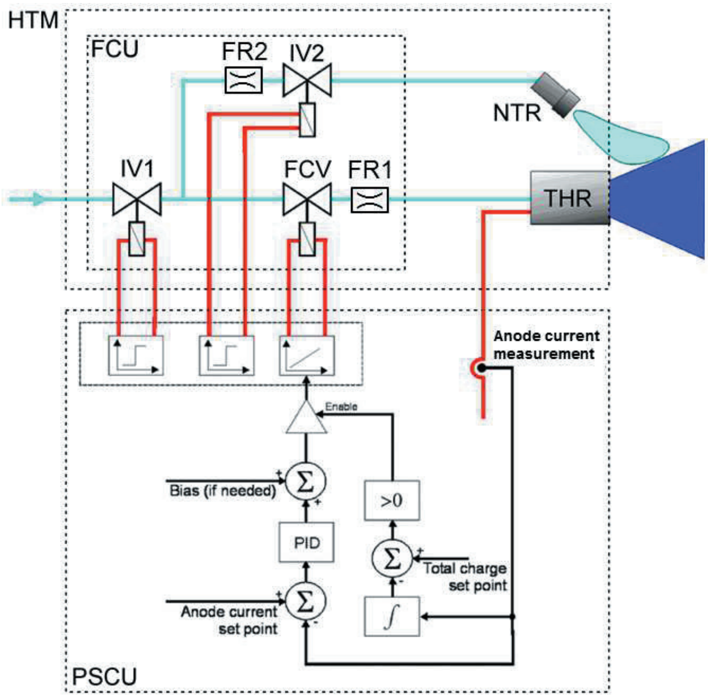

Figure 1. Functional diagram of HTA beam current controller

Propellant supplied to the thruster is controlled within the FCU by the proportional flow control valve (FCV) combined with a downstream flow restrictor. The FCV provides the capability to adjust the flow by means of adjustment of the control current through the valve. The flow resistor provides improved controller stability and limits the gas consumption in case of fully open condition of the FCV. Since thrust and also thruster current is directly proportional to the Xenon mass flow for the HEMP technology, thruster current is measured and used to close the control loop of the beam current regulation. The measurement is performed by the anode current measurement unit and in order to eliminate ripple on the feedback signal, a low pass filter is included in the PSCU. The control loop is closed in the PSCU through the PID regulator and the valve driver. For smooth thruster ignition and predictable start-up, an open loop function is included in the system in order to compensate for the absence of a valid feedback signal. The FCV is opened fully in a pulsed manner whereby the duty cycle is chosen such that an average gas flow around 60% of the throughput of the SGEO/H2Sat operational point is provided. As soon as the PSCU detects the plasma ignition, the controller transients automatically from open loop to closed loop operation.

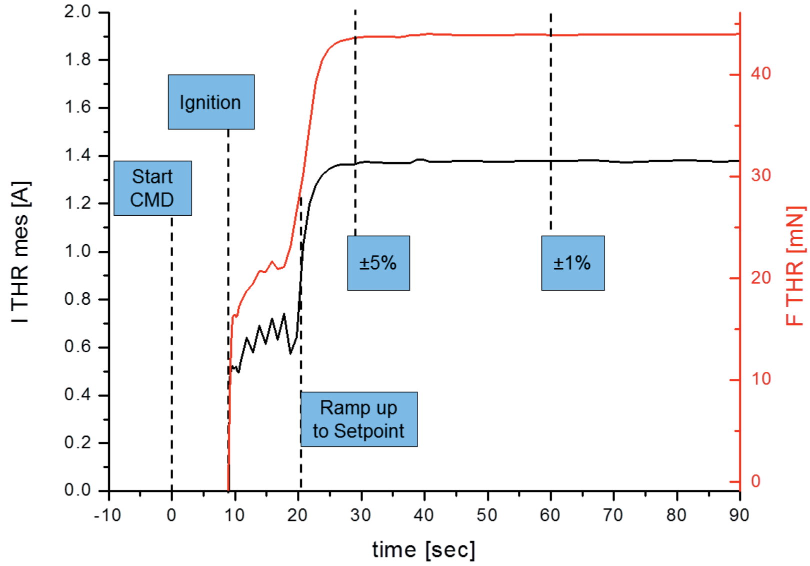

Figure 2. Typical start-up of the HEMP thruster[2]

Figure 2 shows the fast thruster switch on and thrust level capability which can be commanded once the pre-start sequence for the neutralizer is completed. With this concept, 5% thrust precision is given after typically 30 seconds of thrust on command and 1% precision is reached within one minute.

III. Propagation velocity of pressure waves

In order to establish a system-level performance simulation, the dependency of the propagation velocity on the initial condition of the tubing was determined empirically. Consequently, fundamental tests on the propagation velocity of Xenon gas pressure waves in 1/8” tubing were performed. The test case was then reproduced in an EcosimPro simulation environment in order to verify the tubing model for the system-level simulation.

A. Experiment: Filling of 1/8” tubing with Xenon gas

The test setup to determine the propagation velocity consists of Xenon gas bottle, mechanical pressure reducer on the bottle, digital pressure regulator, 6m 1/8” tubing, differential pressure sensor, a flow restrictor, vacuum pump and data acquisition and control electronics. The components upstream of the digital pressure regulator are connected by 1/4” tubing with VCR fittings. The components downstream up to the flow restrictor are connected by 1/8” tubing with known length with either VCR fittings or orbital-welded joints. The pressure sensor and the flow restrictor of the thruster line of the HEMP functional simulator has been used as sensing element for this experiment. Details on the HEMP functional simulator are given in [1]. Since the HEMP functional simulator incorporates a LEE JEVA flow restrictor with the same pressure drop characteristics as the HEMP thruster, representativeness of the test case regarding flow conditions within the HEMP thruster assembly is given. The data acquisition is set to a high sample rate of 100 Hz in order to measure the time difference between valve opening and pressure increase at the flow restrictor sufficiently fast.

The purpose of the test is to measure the propagation velocity of the Xenon pressure wave through 1/8” tubing at different tubing lengths and several initial pressure conditions of the tubing. Two tubing lengths were chosen for this experiment:

- 0.2 m, representing the internal tubing volume of HTM3050 FCU from proportional valve up to the HEMPT 3050 thruster anode.
- 6.2 m, representing a FCU mechanically detached from the Module and mounted to a different location onboard the spacecraft with 6 m tubing between Flow Control Unit and HTM.

The results of the test are summarized in table 1. Evaluated property is the delay time of initial pressure rise at end of tube *t_rise*.

350 mbar was chosen as maximal pressure, since this represents the typical pressure condition in the tubing upstream of the HEMP thruster for the SGEO/H2Sat operational point. For the initial pressure conditions, rough vacuum (named 0 mbar in the table), 50 mbar and 300 mbar were chosen. In order to understand the effect of the pressure amplitude, the following final pressure set points were chosen: 50 mbar, 100 mbar and 350 mbar.

initial pressure, mbar	final pressure, mbar	t_rise, s
0	350	0.64
50	350	0.18
300	350	0.05
0	50	0.65
0	100	0.62

Table 1. Results of delay time measurement

From Table 1 it can be seen that the time for the pressure increase at the outlet *t_rise* is dependent on the initial flow condition in the tubing whereas the effect of the pressure amplitude on *t_rise* seems almost negligible (0.62 s ±0.2 s) for the pressure range measured. In case of evacuated tubing, the gas enters the tubing at molecular flow condition resulting in longer time duration until the pressure wave reaches the end of the tube. At 300 mbar, the propagation velocity is significantly higher and approaches the time propagation duration of local speed of sound $t_s = 0.036\ s$.

B. Simulation of pressure waves in 1/8" tubing

The results from abovementioned test have been used to upgrade the existing tube model by including the delay time of a pressure change moving from the inlet to the outlet. In order to verify the model, the test setup was reproduced in an EcosimPro simulation with the boundary conditions of the Xenon gas coming at from the mechanical pressure reducer at the inlet of the proportional valve (shown on left hand side of the schematics in figure 3). Space vacuum is set as boundary condition at the outlet of the JEVA flow restrictor on the right hand side of the schematics. The digital pressure regulator from the test is included by usage of a proportional valve combined with a pressure sensor downstream. Both components are logically connected by means of a PID controller. A proportional gain is used to simulate the valve driver in this model.

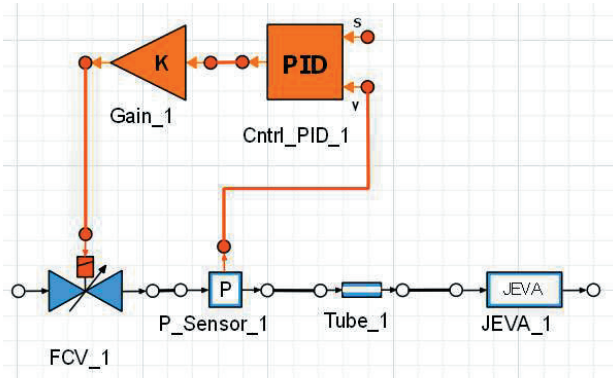

Figure 3. Schematics of simulated experiment on pressure wave propagation velocity

The equation added to the tube model for the delay time is given in equation 1.

$$t_{rise} = l_{tube} \times (0.0631 + 0.0952 \times e^{-3.245 \times p_{init}}) \tag{1}$$

IV. HTA-level simulation

The HTA-level simulation has been verified by comparison to measurements made with the HTA3050 at several operation points. This verification has proven a good representativeness of the dynamic behavior of the simulation. In the next step, the improved tube model shall enable the extension of the HTA simulation to cases where the FCU is separated from the thruster module by several meters of tubing.

C. HTA-level simulation and comparison to experiments

The thruster branch of the HTA is modelled by the relevant components of the FCU and the PSCU, shown in figure 4. The FCU components include proportional flow control valve, the Viscojet flow restrictor, tubing and HEMP thruster. The modelled anode current control logic includes the following PSCU components: anode current measurement unit, filter, PD-controller and integrator with different feedback signal and the HTA logic components required for the typical start up with pulsed, duty cycle controlled actuation of the proportional valve as described in chapter II.

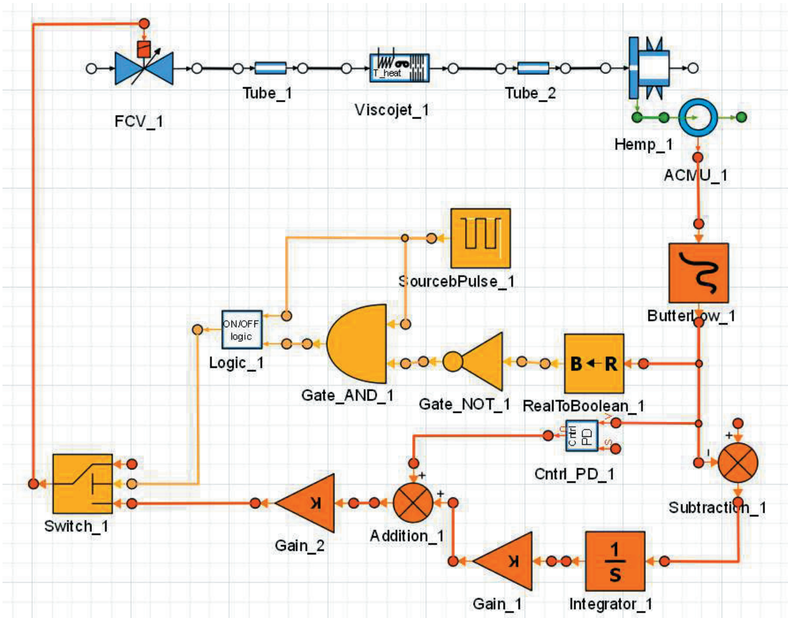

Figure 4. Schematics of experiment on pressure wave propagation velocity

The differential equations of the model have been solved and integrated with 0.01 s time steps for 60 seconds by EcosimPro. The SGEO/H2Sat operation point at 1.38 kW producing at least 44 mN of thrust has been chosen for comparison and the results shown in figure 6 have been generated.

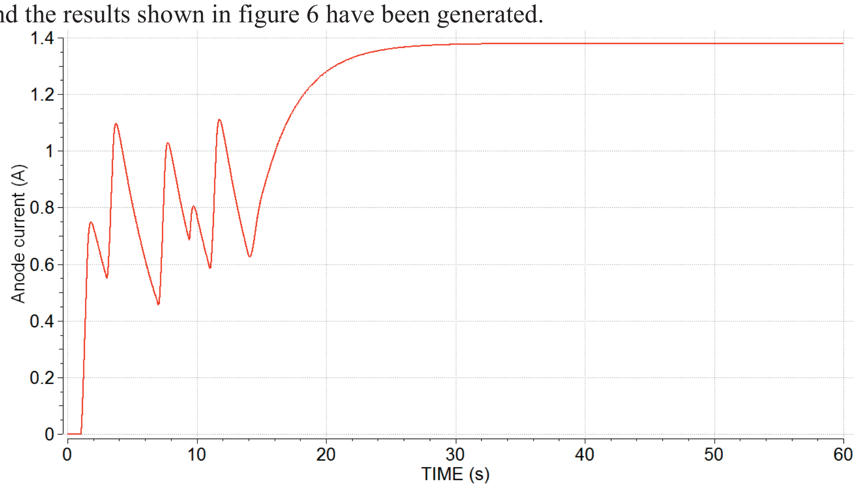

Figure 5. Simulated HEMP thruster start-up

From above figure 5, one can see that the match between experiment and simulation with improved tube model is in good accordance.

D. Simulation of pressure waves in 1/8” tubing

In the next step, the tubing between FCU and HEMP thruster is increased from 0.2 m to 6.2 m. The additional 6 m tubing length is seen as a worst case scenario for a detachment of the FCU from the HTM. With the same boundary conditions and simulation parameters as before, the following HTA start-up performance, seen in the graph of figure 6, is predicted by the model.

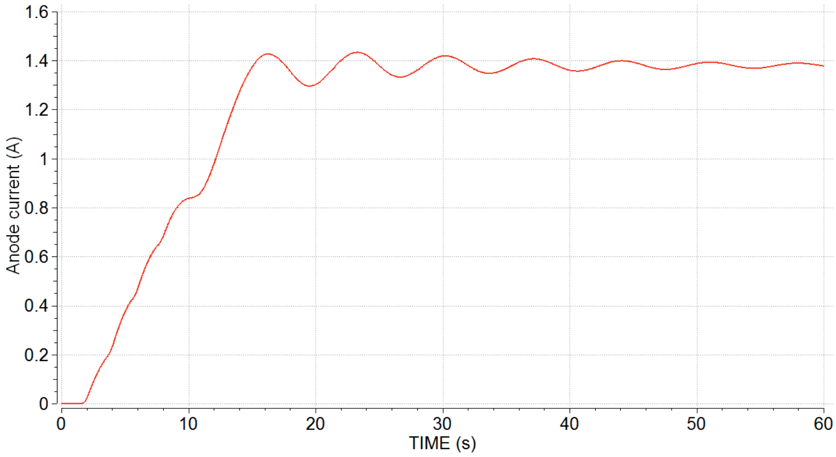

Figure 6. Simulated HEMP thruster start-up

According to these results, the HTA performance exhibits, next to a delayed rise of the anode current, an overshoot up to 1.42 A followed by a damped oscillation. This indicates non-optimal components choice and/or insufficient control parameter properties of the changed system.

The increased dead time due to the additional volume is worsened by the FCU built in delay line, beeing the Viscojet flow restrictor downstream of the proportional flow control valve. With the FCU located directly on the rear side of the thruster module, adding the flow restrictor to the proportional valve provides inreased stability to the thruster branch. This effect is obviously counterproductive with the additional 6 m of tubing in the system. As a consequence, the Viscojet flow restrictor is removed from the HTA simulation and replaced by a straigth tube. The result of this changed design is shown in figure 7.

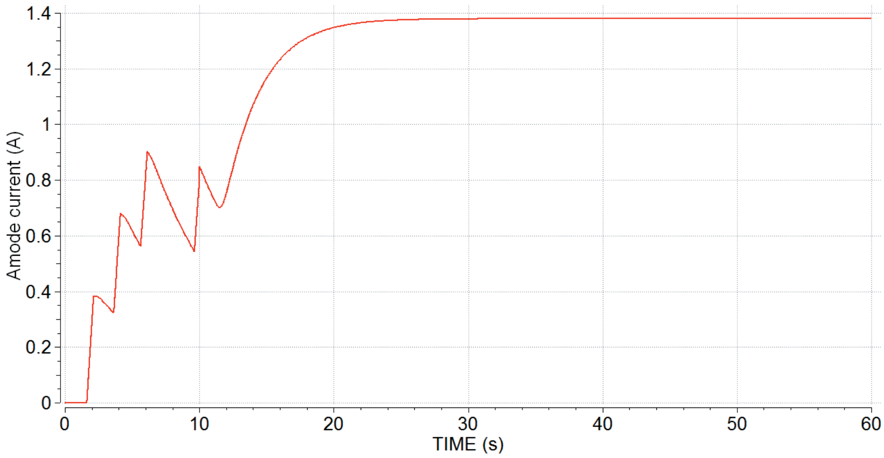

Figure 7. Simulated HEMP thruster start-up

According to the results obtained without the flow restrictor, it can be seen that the start-up performance is back to the original aperiodic convergence of the anode current to the set point at 1.38 A. The start-up at pulsed valve operation still generates an average current of about 60 % whereby the current amplitude is smaller due to the smoothing effect of the additional volume.

V. Conclusion

Thales has matured the HTA3050 design to TRL7 and the HTA-QM is going into lifetime qualification test in order to reach level 8. In parallel, the HTA-FM is intended for its inauguration flight on the German Heinrich Hertz satellite mission to reach the final level 9. Work packages to show compatibility of the HEMP electric propulsion system towards other satellite missions have been initiated. The separation of the Flow Control Unit from the thruster module is one possible accommodation option.

This paper has presented the HTA simulation and the results produced by this system simulation. One finding usable for the electric orbit raising development, where the FCU is separated from the HEMP Thruster Module by several meters of 1/8” tubing, is that simply removing the thruster line flow restrictor from the FCU results in restored HTA performance. The replacement of the thruster line flow restrictor by a straight tube with the same length would not even require FCU or PSCU redesign let alone delta-qualification of these units.

The next steps are firstly to check HTA-level simulation by an experiment with additional tubing length between FCU and HEMP thruster. Secondly, key components of the HTA3050 such as the HEMP Thruster itself are intended to be the implemented into the EcosimPro European Space Propulsion System Simulation (ESPSS) data base.

Acknowledgments

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[2] S. Weis et al.; Architecture, Functional Features and Operational Characteristics of the HEMPT based Ion Propulsion System for SmallGEO IEPC-2011-223.