IN-FLIGHT DISTURBANCE TORQUE EVALUATION OF THE SMART-1 PLASMA THRUSTER

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ABSTRACT

This paper presents the results of an evaluation of flight data from SMART-1 aiming at improving the knowledge about the behavior of Hall Effect thrusters and their impact on the S/C dynamics.

This type of thruster is characterized by a small parasitic torque component around the line of thrust – so-called swirl torque - that cannot be compensated directly by mounting the thruster on an alignment mechanism.

Analytical estimates indicate a torque in the order of up to few tens of micro-Newton-meters. Unfortunately however, an accurate theoretical prediction of this swirl torque is not possible and measurements on ground are too difficult and expensive.

Therefore an evaluation of flight data is the only practical way to better characterize this thruster for future users.

1. THE SMART-1 MISSION

The SMART-1 mission was launched on September, 27th 2003 from Kourou as third passenger on board an Ariane 5. Its name (Small Mission for Advanced Research and Technology) indicates that it is the first of a series of ESA missions aimed at testing and qualifying new technologies to be used on future Cornerstone missions.

SMART-1 is the first European satellite using Electric Propulsion (EP) as main propulsion system. Its first mission target is to demonstrate the capability of the EP to transfer the spacecraft from an Earth geostationary transfer orbit (GTO) into a Moon polar orbit, where the scientific payload will perform a six months Moon surface observation.

The S/C is expected to reach the Moon along a so-called low-thrust trajectory, consisting in a first phase of spiraling away from Earth by using the EP thrust and, after a series of Moon gravity assisted maneuvers and the transition in Moon orbit, a second phase of spiraling but this time aiming at decreasing the distance from the Moon.

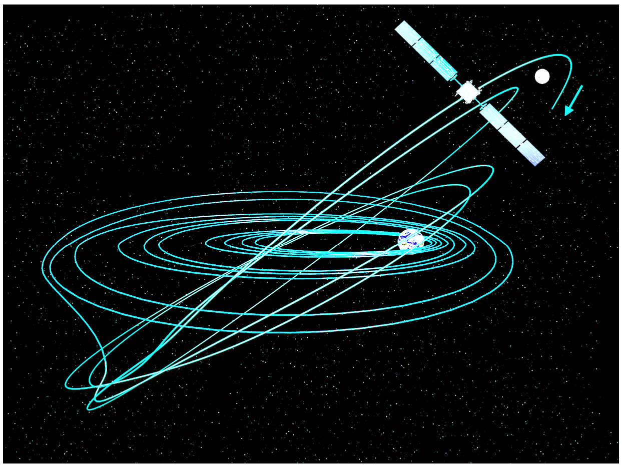

Fig. 1.SMART-1 low thrust trajectory to the Moon

1.1 Current position

At the moment the S/C is still in Earth orbit and it is planned to pass into Moon orbit during the next mid November 2004 [see ref. 3]. As of mid September, the S/C had reached an orbit with pericentre about 42000 km, apocentre at about 268000 (i.e. semi-major axis of about 155000 km, eccentricity of 0.73), inclination of the orbital plane of 7.6 deg and a revolution period of about 169 hours / 7 days].

1.2 Electric Propulsion system

The selected Electric Propulsion system for SMART-1 is of the Hall-Effect type, also called Plasma thruster; the PPS-1350-G is produced by SNECMA Moteurs in France. For SMART-1, the nominal thrust has been limited to70 mN for a total system power requirement of about 1418 watts (including margins).

As a main feature of the Smart-1 program, the thruster is able to be started and operated at a variable discharge power in order to limit power transients, cover several failure cases and accommodate the solar cells performance degradation.

Anyway, most recent flight data indicate that the Solar Arrays are working at a level of efficiency higher than expected with a consequent increase in power availability.

The xenon propellant flow is regulated in pressure with an electronic bang-bang system and the mass-flow-rate is controlled via a closed-loop with the thruster discharge current as target.

1.3 AOCS & EPMEC

In the SMART-1 case, the AOCS relies essentially on the Star tracker measurements when the S/C is in nominal operation modes and make use of the gyros only when the Start trackers data are invalidated by the FDIR (Failure Detection Isolation and Recovery system) or for emergency modes.

The compensation of the disturbance torques acting on the S/C is achieved by the combined actions of the RWs and -when the EP is on- by the EPMEC.
EPMEC stands for EP MEChanism and consists in a 2-axis gimbal on which the EP thruster is mounted. It can depoint the thrust vector from the nominal S/C Z-axis around the S/C X- and Y-axes of up to 10 deg along each direction. This mechanism allows to minimize the disturbance torques by aligning the thrust vector with the spacecraft center of mass. In addiction, being actively used in an onboard control loop, it can also generate control torques for a continuous reaction wheels desaturation.
Then the EPMEC system was found extremely convenient from the fuel budget point of view, allowing to off-load during EP-on phases most part of the angular momentum stored by the RWs around S/C X- and Y-axes and thus minimizing the hydrazine consumption for that purpose.

2. INPUT DATA

During the second phase of the Earth escape trajectory, ground control started to record an increasing number of automatic RW wheels off-loadings. These events resulted as a consequence of a momentum build-up on the Z-axis, which could not be removed by the EPMEC actuation during this phase of the mission, being the EP active only partially along the orbit.

It was then decided to retrieve the flight data i.e. telemetry of the S/C body rates together with RW speeds (wheels momentum) and the EPMEC gimbal angles and to perform an evaluation of the torque acting on the S/C Z-axis before, during and after an active EP phase.
Since the S/C body rates are generated onboard by a Kalman filter processing the star trackers and gyros information, they are affected by a very strong noise originating from the low cost, solid state gyros used on this mission. Due to this strong noise content, filtering and/or averaging methods have to be applied to the input and/or to the output signals. This was done for various sets of data collected during very different times of the mission, ranging from December 2003 to July 2004, and thus with distances from Earth varying from less than 20000 km to about 270000 km.

The following graph [figure 2] presents the RW Angular moment behavior during a typical long thrust arc (about 20 hours) as it appeared to the ground control. It starts from an EP-off phase, going through the EP switching-on and then concluding with the RW off-loading activation (not shown in the graph), which is performed by firing the hydrazine thrusters:

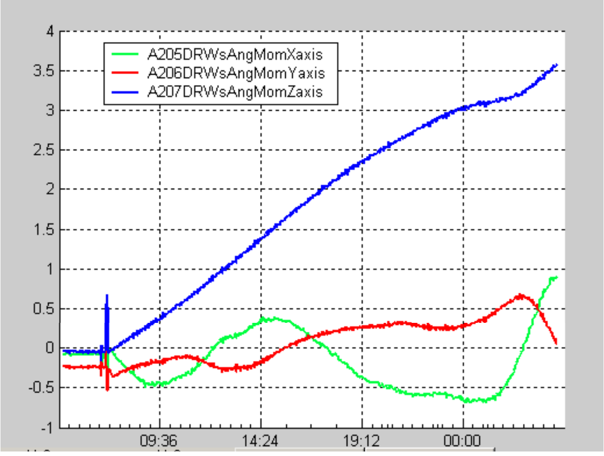

Fig. 2. RW angular momentum during active EP phase (growing value is RW Ang Mom Z-axis)

3. FLIGHT DATA EVALUATION RESULTS

3.1 Swirl torque effect on S/C dynamics

The so-called swirl torque has the peculiarity of being created around the EP thrusting line by an electromagnetic field.

As a result, referring to the S/C body frame, the X-Y components (if any) of this disturbance are compensated by the EPMEC as well as all other disturbance torques along those axes, whilst the Z component is left unbalanced and accumulates in the RWs. This overall behavior is highlighted in the Fig. 2, where the projections along the S/C X and Y axes of the RW angular momentum are oscillating around zero value, while the third component is constantly growing, clearly suggesting the presence of a quite constant torque around Z-axis.

A major point to be observed is that the total contribution of the swirl torque to the S/C (or RWs if they are absorbing it) angular momentum over a full orbit with continuous thrusting can be made null. In fact while it is true that this torque is not immediately controllable by the 2-axis gimbal i.e. EPMEC, it is also true that this is possible (as applied during the first phase of the SMART-1 mission) in those cases where the wheels provide sufficient momentum storage capacity and the attitude profile along the full orbit ensures a migration of the stored Z-axis momentum into the other S/C axes, which are instead controllable by the gimbal.

3.2 Swirl torque evaluated value

The evaluation of the telemetry is then focused on the reconstruction of the torque acting around S/C Z-axis based on the S/C rates.

The main problem with this method is represented by the consistent noise associated to the rates measurements. Since this is reflected in the resulting torque calculation, it has been decided to apply an averaging function for each thrusting period. The result is that an average swirl torque of about 54 to 62 μNm is regularly appearing during the EP-on phases. This result is in line with the analytical estimates provided by the thruster manufacturer (SNECMA) [see paragraph 3.3].

As expected (and giving credit to the averaging method) the average torque around SC Z-axis during periods without EP activity was found to be substantially null (±1 μNm).

3.3 Swirl torque origin

The origin of the swirl torque is due to the radial magnetic field component in the exit of the discharge channel of the hall thruster, which generates an azimuthal velocity component on the accelerated ions. This in turn creates a reaction torque on the S/C around the thrust line. The actual direction of this torque depends on the effective polarity of the magnets for a given thruster assembly.

The predicted value of the thruster azimuthal torque (i.e. swirl torque) at 70 mN is equal to 58 μNm and is expected to be proportional to the thrust level.

3.4 Current compensation strategy on SMART-1

The current strategy chosen for the SMART-1 mission is to program the onboard computer to activate the RW off-loadings every 15 hrs of continuous EP thrusting [see ref. 3] in order to avoid the accumulation of the RW angular momentum around S/C Z-axis reaching its maximum value (when the automatic momentum management function is activated) and so keep all the wheels away from their saturation limit.

3.5 Mitigation strategies approach and further investigation lines

The major point of interest for the future applications of this kind of EP thrusters is the approach to the torque compensation strategy. It has already been mentioned that the impact of the swirl torque on the S/C dynamics during complete EP-on orbits can be cancelled. The following graph [figure 3] shows the behavior of the RW angular moment along a full thrusting orbit during the first period of the mission (in particular 25th-26th December 2003). It can be observed that the RW angular moments accumulated over a complete orbit period was null. This is the consequence of the principle explained in paragraph 3.1.

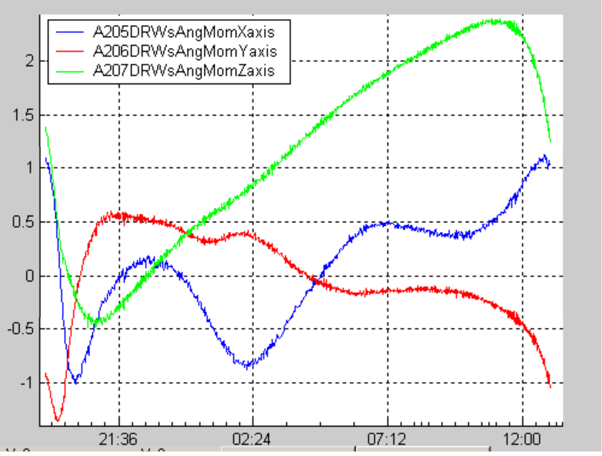

Fig. 3. RW angular momentum during active EP phase along a full thrusting orbit

This implies that the first option to compensate the presence of this disturbance is at mission/trajectory design level.
An application of this technique is represented by missions (typically telecommunication) including a transfer from GTO to GEO: the swirl torque could then be averaged out during the spiraling phase as demonstrated by SMART-1.

Where this criteria is not applicable, the other way to compensate the angular momentum accumulation is by the classic actuation methods. In this frame the RWs (as the example of SMART-1) seem the most obvious solution, but present the drawback of increasing the fuel budget, while the magnetic torquers devices would impact only on the power budget, but are not suitable for extra LEO missions.
As explained in the paragraph 1.3, the mounting of the EP on a gimbaled system structured as the SMART-1 EPMEC solves efficiently the problem of the torque components projected in the plane perpendicular to the S/C Z-axis but leaves the third component substantially unbalanced and so it cannot be used for the purpose of the swirl torque compensation.

From the point of view of electric propulsion, the swirl torque can be suppressed when two thrusters are operated in parallel by having opposite magnetic polarities on each thruster. This specific requirement would only be needed in case the swirl torque cannot be averaged out over an orbit.

4. CONCLUSIONS

This paper presents the results of an evaluation of flight data focusing on the parasitic torque component around the line of thrust – so-called swirl torque.

The existence of this component was derived by the elaboration of the S/C telemetry, which highlighted the presence of a constant torque along the S/C Z-axis during the active EP phases and was found consistent with the analytical estimates provided by the thruster manufacturer (SNECMA).

Although originated by the electromagnetic field of the EP thruster, the swirl torque has to be treated as other disturbance torques with the only peculiarity of being generated by and along the EP thrust vector.

Depending on the mission, i.e. the long-term inertial orientation of the thrust vector during the thrust maneuvers, this so-called swirl torque may have a non-negligible impact on AOCS design, mission operations and fuel consumption for unloading momentum or reaction wheels.
Since the swirl torque is an inherent feature of the Hall-effect thruster, some mitigation methods have already been identified [see previous paragraph] and allow minimizing or even canceling the impact of this side effect on the S/C dynamics.

5. REFERENCES

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