EXPERIMENTAL AND NUMERICAL STUDY OF DISTURBANCE FORCES INDUCED BY A SPT100 PLASMA JET

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Abstract

The interactions of plasma jet with spacecraft surfaces are not yet precisely known. Electrical effects involve surface potential modifications and mechanical effects lead to surface deterioration through material erosion and sputtered particles re-deposition.

Disturbance forces induced by plasmic jet on spacecraft surfaces have to be taken into account in the Attitude and Orbit Control System. Very few data exist to quantify these effects. An experiment has been carried out to measure disturbance forces induced by the plasma jet on a representative solar array sample. A mechanism has been thought out to enable the measurement of tiny forces from 0.5 mN to 80 mN.

The results are correlated to the numerical values calculated by the software ISP (Interaction Software for Propulsion). This software has been developed in collaboration between ALCATEL and MAI (Moscow Aviation Institute, Russia). The comparison between the experimentation and the numerical model exhibits a quite good agreement.

Experimental part

The experiments have been achieved at Orléans in the Laboratoire d’Aérothermique of CNRS (Centre National de la Recherche Scientifique).

The PIVOINE® (Propulsion Ionique pour les Vols Orbitaux - Interprétations et Nouvelles Expériences) chamber has been used to carry out the tests. These test facilities are dedicated to specific tests with SPT100-ML, a thruster specially designed by SEP. Annex I presents a view of PIVOINE test facilities.

For the dynamical tests, the thruster has been activated with the following nominal SPT100 parameters:
- discharge voltage: 300 V
- discharge intensity: 4.5 A
- xenon flow rate: 5.4 mg/s
- xenon pressure: 2.5 $10^{-3}$ mbar

The sample and its mechanism

The experiments consisted in locating a sample representative of a solar array in the plasma jet for various positions. A position is defined by two angles: divergence $\theta$ and incidence $\phi$ as shown on the figure below.

The sample is part of a pendular mechanism which is fixed on a beam in the PIVOINE chamber. This moving system allows a translation movement along an axis orthogonal to the plasma jet axis in the equatorial plan of the thruster. The thruster is fixed on a beam which can translate along the longitudinal axis of the chamber. The combination of both axes movements permit to get the desired divergence angles. The incidence angles are obtained through a rotating plate which holds the sample.

The fixed parts of the mechanism are protected from the plasma jet with graphite plates.
The sample is constituted of aluminium honeycomb with carbon skins, covered with kapton film and coverglass rectangular plates. The main constraints concerning this sample were its light weight combined with a rather large surface in order to measure sensible deviations of the sample even in high divergence angles where the plume density is rarefied. Its weight is about 200 g and its dimensions are 300 x 300 x 10.4 mm.

Normal and tangential forces to the sample plan are estimated from the rotation angles α, β recorded by inclinometers.

Views of the mechanism including the sample are presented in Annex 2.

The test procedure

Preliminary tests were performed in order to define the test procedure. The main problem is the sample and mechanism heating due to the proximity of the thruster exit (500 mm), which can disturb the measurements. For that purpose, ceramic parts were stuck to the sample to minimize heat transfer with the sensible parts like inclinometers. Besides, as the sample materials degenerate with temperature, time exposition to the jet must be constrained to the minimum. The following procedure was applied during the dynamical tests:
1. Thruster ON and stabilization at its nominal functional point for 1h30.
2. Thruster OFF.
3. Positioning of the sample at the desired divergence θ and incidence φ.
4. Waiting for the sample stabilization to reset the inclinometers.
5. Thruster ON.
6. Measurements of deviation angles α, β during a maximal time of 1 mn for divergences 0 et 15° or for a longer time for divergences 30° and 45°.
7. Sample in rest position in the chamber for 10 mn to allow the sample cooling and the discharge current stabilization.
8. goto step 2.

The intended positions for the sample have been applied. Each position corresponds to a couple (θ, φ) with the following values for these angles:
θ = 0°, 15°, 30°, 45°
φ = 0°, 15°, 30°, 45°, 60°

Tests results

Even in high divergence cases for which the sample is exposed to a very little energetic part of the plasma jet, inclinometers succeeded in recording the very slight angular deviations (down to 0.02°).

The curves showing the evolution of the tilt angles versus time present successively three distinct parts:

- from time = 0 till the thruster firing, reset of the inclinometers.
- thruster firing : tilt increasing till stabilization
- positioning of the sample in stop position : decrease of tilt back to 0°.

On the time evolution curves of α and β angles, two kinds of stabilization of the sample around a mean tilt occur (two examples are shown in Annex 3):
- either the tilt increases slowly and tends towards a stabilized value.
- or the tilt varies very abruptly and gets stabilized very quickly at its mean value.

A mechanical calibration process has been set up to recover the forces from the recorded deviation angles. This involves simply pulleys and some few grams calibrated weights.

Each sample position has been tested twice : the reproducibility is quite good since the gap is less than 15 % for significant angles. A mean force is deduced from the two measured values.

The uncertainty related to the whole chain of measures can be estimated at ± 0.01° for tilt.

The evolution of these mean forces versus incidence angle is presented hereafter for the four divergence angles.
Numerical Part

The experimental results have been compared with numerical results obtained with the software ISP (Interaction Software for Propulsion).

Software overview

ISP has been developed in collaboration between Alcatel Space Industries and Moscow Aviation Institute to quantify the interactions between a plasma jet and spacecraft surfaces. It is capable to predict disturbance torques and forces, surface heating, erosion and re-deposition of sputtered materials.

Plasmic plume is modeled through fractions of monoenergetic ions (both Xe+ and Xe++). The source point model including density variation versus jet divergence angle is taken as numerical model to describe the spatial expansion of particules from the thruster exit. The forces are analytically defined by a model of exchange processes using accommodation coefficients.

The particles spatial density, current density and energy have been correlated by several SPT ground tests. Testings have been carried out by Alcatel Space Industries in Russia to assess sputtering rates on specific spatial materials. Some published experiments have shown a good correlation between predicted and measured heating. The final point to validate ISP software was to verify the prediction of interaction forces.

Correlation

The following curves present the measured and predicted forces obtained after adaptation of accommodation coefficients.

The remaining discrepancies may be explained mainly by the thruster characteristics. Indeed, ISP SPT100 plume has been correlated with testings performed at MAI with another SPT100 that provides a more divergent jet with more charge exchange ions.

The correlation between predictions and measurements is better than 13% for normal forces and 7% for tangential forces where the modeled plume is similar with testing jet.

Conclusion

This achieved new experiment has enabled Alcatel Space Industries to secure data on disturbance forces and torques due to thruster plasmic jet on solar array. All software ISP predictions are now correlated by testings and future satellites will benefit from this experience.

References

ANNEX 1 : P.I.V.O.I.N.E test facilities
ANNEX 2: mechanism and sample
ANNEX 3: two examples of deviation angles recording

\[ \theta = 15^\circ, \phi = 45^\circ \text{ (top)} \]
\[ \theta = 45^\circ, \phi = 15^\circ \text{ (bottom)} \]

Point: a21545  Alpha moyen = 0.6527°

Point: a21545  Bêta moyen = 0.4769°

Point: a24515  Alpha moyen = 0.1185°

Point: a24515  Bêta moyen = 0.03105°