Direct Thrust Measurement of In-FEEP Clusters

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Thrust measurements of electric propulsion devices are essential for validating, characterizing and qualifying their performance. For this purpose a direct thrust measurement system for use with In-FEEP thrusters has been designed at ARC Seibersdorf research (ARC-sr), based on a torsional balance design. In the scope of the ongoing developments of ultra precise FEEP thrusters a 2x2 cluster based on new technologies has been manufactured and is currently being tested. The µN thrust balance has been adapted to allow the cluster to be mounted and tested. New improvements like the use of a stepper motor for positioning of the precise distance sensor and the use of a second flight representative DC/DC converter for biasing the cover plate of the tested thrusters as well as an improved software for the analysis of the data have been utilized during the latest tests.

I. Introduction

Indium Field-Emission-Electric-Propulsion (FEEP) is an high specific impulse electrostatic propulsion concept developed at ARC Seibersdorf research (ARC-sr)[1]. The ion source consists either of a needle covered with Indium or a capillary with Indium inside, which is heated above the Indium melting point (156.6 ºC). Then a sufficiently high electric potential is applied between the emitter and an extractor electrode until a field strength of 10^{10} V/m is reached at the tip. A so-called Taylor cone, with a jet protruding due to space charge, is formed as the surface tension and the electric field strength reach equilibrium. Atoms are then ionised at the tip of the jet and accelerated out by the same field that created them. The expelled ions are replenished by the hydrodynamic flow of the liquid metal.

This Indium Liquid-Metal-Ion-Source is used on several satellites to provide potential control of satellites (e.g. CLUSTER-II) or as the core of a mass spectrometer (instrument COSIMA on ROSETTA). Since 1995, this ion source is being developed as a dedicated low-thrust propulsion system for ultra precise attitude and orbit control.

Thrust measurements are an essential part in the characterization and qualification process to evaluate the performance of electric propulsion devices. Several methods have been used to determine the thrust of an In-FEEP thruster. These include the calculation of thrust from measurements of current and voltage. This calculation uses a so called c- factor which accounts for the beam divergence. The accurate measurement of this factor is one of the main goals from the direct thrust measurement. Providing an in-house capability to measure thrusts in the micro-Newton range is beneficial to the ongoing developments of In-FEEP thrusters. For this purpose a direct thrust measurement system for electric thrusters operating in the micronewton thrust range has been designed at ARC-sr. Recently the design of the balance has been published[2]. In the meantime the balance has been mechanically adapted to allow the measurement of a 2x2 In-FEEP cluster.

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II. Thrust Balance Description

The balance consists of a symmetric arm (a hollow rectangular aluminum profile with a side length of 20mm and a total length of about 60cm) which is free to rotate by means of two flexural pivots (see Fig. 1). The pivots have been selected because of their low friction, high linearity and negligible hysteresis. In addition they are able to support large loads (in the order of a few kilograms). When the thruster, which is mounted to one end of the arm is switched it will exert a force on the arm, causing it to shift its position. The deflection of the balance is a linear function of the applied force. The sensor, a Philtec D64 fiber optic displacement sensor can be repositioned using an OWIS precision stage driven by a vacuum compatible stepper motor. Using this assembly the initial setup is made much easier as the position of the sensor can be conveniently controlled from the outside using a custom made software. The typical response curve of the sensor allows the operation of the sensor in either the so called ‘near side’ or the ‘far side’. The near side offers a higher sensitivity at the cost of a decreased linear measurement range. The far side has a worse sensitivity but a much larger measurement range. Using the stepper motor the working point of the sensor can be changed from near to far and the sensor can be repositioned in case of a drift of the balance arm.

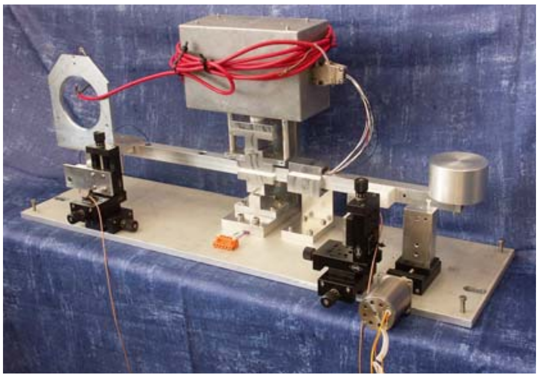

Figure 1. ARC-sr µN thrust balance

To minimize disturbances caused by the high voltage lines to the balance it has been decided to supply the balance with low voltage connections only and to mount a HV DC/DC converter directly on the balance. It consists of two CAEN flight model DC/DC converters. A S9071 (+11kv, 0,7mA) converter is used as primary supply for the thruster while a S9032F (-1kV, 1mA) converter is used to provide a fixed voltage of -1KV to bias either the cover plate or the extractor of the thruster. Both converters are supplied with a fixed voltage of 28VDC and offer several voltage control and monitor lines.

For the analysis of the data new software has been written to process calibration and real thrust measurement data. The program enables the measurements to be analyzed with minimal user input and provides results as well as statistical data.

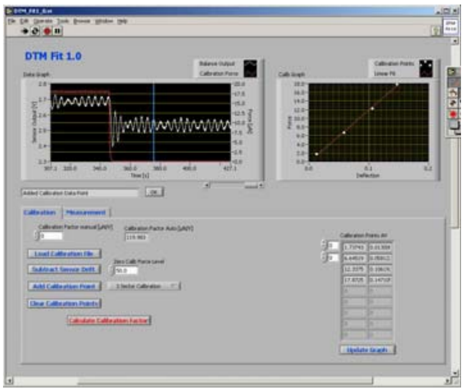

Figure 2. Screenshot of data analysis software

III. 2x2 In-FEEP Cluster

A single In-FEEP ion emitter has a maximum continuous thrust level of 10 µN. In order to fulfil the thrust requirements of missions like LISA Pathfinder (75-100 µN), it is necessary to cluster a certain number of emitters. The new 2x2 Cluster Breadboard[3] was developed as an upgrade of the already existing 2x2 module design. The main improvements are the direct high voltage feeding to the focusing electrodes (direct connection with the respective emitter, no external connections required), spring connectors for the extractor and cover-plate, a new concept for heating the propellant, and integrated electronics for cluster operation. The cluster holds four in-FEEP ion sources with 15g of propellant each. Its diameter is 136mm and the length (including the electronic box) is 125mm. The mass of the cluster assembly is approx. 1300g. The cluster is shown in Fig. 3.

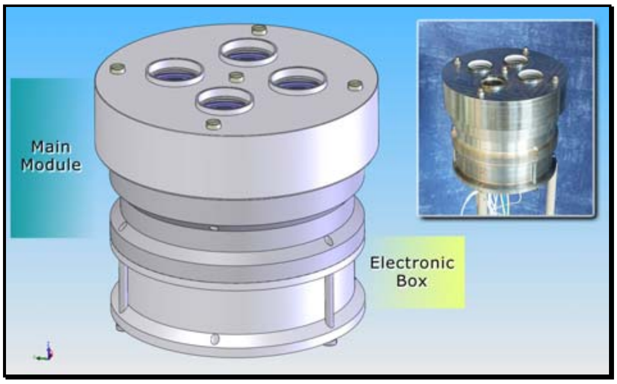

Figure 3. 2x2 In-FEEP Cluster Module

One key feature of the 2x2 cluster is the ion beam focusing system. An important effect of a focusing electrode is the increase in thrust. Since only the speed component of the ions that is parallel to the center of the beam contributes to thrust, a smaller divergence angle is preferable. Reducing the beam divergence half angle from 60° to 25° results in a significant (up to 17%) increase of thrust.

Before the thruster was mounted on the balance it has been tested in a 600h endurance test. During the test the thrust was stabilized using a software controller. The cluster has been operated between 0 and 45µN.

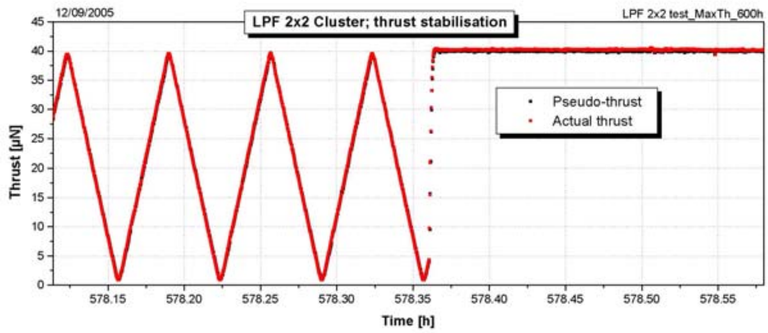

Figure 4. 2x2 Cluster Thrust during 600h endurance test

IV. Measurements

A. Single In-FEEP Emitter

In a first test a single In-FEEP mounted in a standard module has been tested. The tested emitter was a TR14, a new emitter type manufactured from tantalum with a propellant capacity of 15 grams. After a test run, in which the function of the emitter was verified it was mounted on the balance. The module used was equipped with an isolated cover plate that was biased to -1kV to repel secondary electrons. An assembled In-FEEP thruster like the one used for testing is shown in Fig. 5.

Figure 5. In-FEEP thruster Module

Before any measurement using the thruster can be done, the balance has to be calibrated. This is done by applying a known force and measuring the response of the balance. In the present system the force is applied using a pair of electrostatic comb actuators, mounted beneath the thruster, at the same distance from the center of rotation. An example of the calibration data with the single module mounted on the balance is shown in Fig. 6.

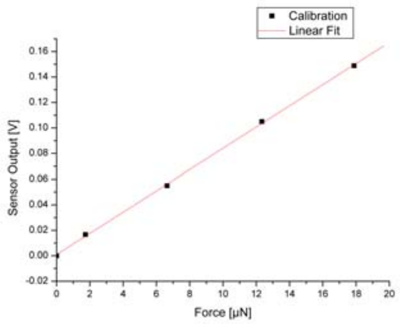

Figure 6. Single emitter calibration data

From the calibration data one can calculate a calibration factor of 120.217 µN/V. The linear relationship between applied force and deflection can be easily seen.

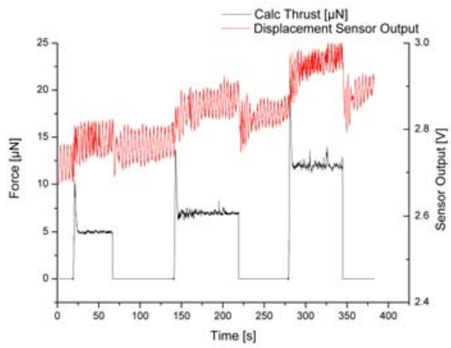

Figure 7. Example of raw data from thrust measurement

In Fig. 7 the raw data from the measurement can be seen. This data is analyzed using a custom built software. After reading a data file any drift of the sensor can be calculated and is automatically subtracted. The software analyzes every step (from low thrust to high thrust and vice versa) and returns the thrust calculated. This calculation is based on the calibration of the balance (see above). The thruster on the balance is regulated using a software implemented PID controller. By calculating the commanded thrust (based on measurements of voltage and current and assuming a c-factor of 1) and measuring the thrust, the c-factor can be calculated.

Mean calc thrust [µN]	measured Thrust [µN]	measured c factor
4.94	4.37	0.88
4.98	4.77	0.96
4.97	4.46	0.90

Table 1 First thrust measurement results

Although these are only first measurements that can for sure be optimized, the results are similar compared to ones measured with other thrust balances and a beam diagnostic system.

B. 2x2 In-FEEP Cluster

A special adapter was manufactured to allow the 2x2 cluster to be mounted on the balance and to keep the center of gravity over the arm of the balance in order not to produce additional torques on the system. The mounted cluster can be seen in Fig. 8

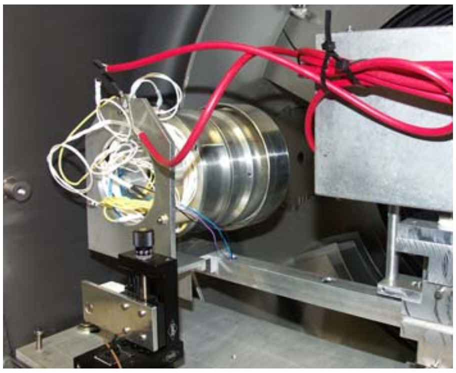

Figure 8. Cluster Module mounted on the balance

The increased mass of the module required additional counterweights to be mounted on the opposite side of the arm. The increased mass led of course to an increased period of the balance. A first test showed some problems when operating the cluster. Biasing the cover plate to -1kV produced a shift in the balances resting position equivalent to about 5µN of thrust. This effect was not seen when biasing the cover plate of the single emitter module, but probably can be explained to the larger size of the module and with that the decreased distance to the grounded chamber walls and the aluminum collector inside the chamber.

Due to the limited availability of the used vacuum chamber (it is normally used for endurance tests of the In-FEEP clusters) only a few short measurements could be done. Especially a problem with the vacuum chamber limited the time available and because of too high pressure made accurate measurements impossible. We expect to increase accuracy by doing more measurements and some improvements in the analysis of the data and the mechanical setup of the balance.

V. Conclusion

The existing thrust measurement facility at ARC-sr is being used for the qualification of In-FEEP thrusters. Up to now, measurements have only been made using single In-FEEP emitter modules. Recently a 2x2 cluster has been manufactured to test technologies needed for missions like LISA Pathfinder. These technologies include new electronics for the clustering of emitters and a novel beam focusing system which increases the thrust by up to 17%. This cluster has been mounted on the µN thrust balance. First tests show that the balance is capable of supporting the heavier cluster and measuring the thrust it produces. Due to some unexpected problems with the equipment, additional work is required before the targeted resolution can be reached and more results can be published. One of the next steps is the measurement of thrust noise as required by many missions. Because the vacuum chamber with the thrust balance is located in a noisy laboratory this may require additional hardware for damping the vibrations.

In addition to measuring the continuous thrust of In-FEEP emitters it is planned to measure also pulsed thrusters like PPTs.

Acknowledgments

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