Development of BUSTLab Thrust Stand for mili-Newton Level Thrust Measurements of Electric Propulsion Systems

IEPC-2017-317

Presented at the 35th International Electric Propulsion Conference
Georgia Institute of Technology – Atlanta, Georgia – USA
October 8–12, 2017

Ugur Kokal* and Murat Celik†
Bogazici University, Istanbul, Turkey

A thrust stand is designed and built at BUSTLab (Bogazici University Space Technologies Laboratory) for thrust measurements of electric thrusters. Inverted pendulum configuration is utilized, and thruster mass is balanced with counterweights. Thrust forces at mili-Newton levels can be measured with a resolution of ∼100 micro-Newton levels. Measurement range and sensitivity can be adjusted according to the thrust level of the thruster, by adjusting the thrust stand components and counterweights. Displacement measurements are conducted between the upper and lower parts of the pendulum mechanism, so that effects of external perturbations on the measurements are reduced. In-situ calibration can be performed by using a pre-calibrated load cell. Initial measurements are conducted with HK40 Hall thruster and M'crowave Electrothermal Thruster (MET) developed at BUSTLab.

I. Introduction

Electric propulsion systems can be separated into three main categories: electrostatic, electromagnetic and electrothermal propulsion systems.[1] Each category has different thrust and specific impulse levels. The achievable thrust levels of the electric propulsion systems are much lower than chemical propulsion systems, therefore conventional thrust measurement methods cannot be applied to the electric propulsion systems. Also the thrust to mass ratio is very low at electric propulsion systems; therefore the thrust measurement systems for electric thrusters have to be designed so that the thrust force of the thrusters can be differentiated from the weight of the thruster. Pendulum based thrust stands have been developed to achieve this goal. The thrust vector and the gravity vector can be separated in a pendulum mechanism, thus very low thrusts can be measured without being affected from the weight of the thruster.[2]

Several pendulum configurations have been developed for thrust measurements of the electric propulsion systems. These are hanging pendulum, inverted pendulum and torsional pendulum mechanisms.[3] In a hanging pendulum configuration, the thruster is mounted on the bottom of the pendulum arm. In an inverted pendulum configuration, the thruster is mounted on the top of the pendulum. While the gravity vector of the thruster is perpendicular to the thrust vector in hanging and inverted pendulums, which have vertical pendulum arms, gravity vector is parallel to the thrust vector in a torsional pendulum configuration. In torsional pendulum, the thruster and a counterweight is placed on a horizontal pendulum arm. Each configuration has different advantages and disadvantages.

Different thrust stand designs have been built at univeristies and research centers for thrust measurements of electric propulsion systems. A significant example is the thrust stand developed at NASA Glenn Research Center. That thrust stand utilizes an inverted pendulum configuration.[4] The structure of the thrust stand consists of two parallel pendulum arms, and is kept at stationary position by an active control system.

*Graduate Research Assistant, Mechanical Engineering Department, ugur.kokal@boun.edu.tr.
†Associate Professor, Mechanical Engineering Department, murat.celik@boun.edu.tr.

Another thrust stand that is based on inverted pendulum configuration is developed by DLR Goettingen Electric Propulsion Test Facility.[5] The thrust stand utilizes a double armed counterbalanced thrust stand. The double armed pendulum configuration avoids the changes in the direction of the thrust vector during the operation. As examples for hanging pendulum configurations, thrust stands that are designed by Astrium GmbH and ONERA can be given.[6,7] Both thrust stands are designed for thrust measurements at micro-Newton levels.

II. Thrust Stand Design

The thrust stand that is built at BUSTLab is based on inverted pendulum configuration (Fig. 1). Inverted pendulum mechanism provides a compact structure, which is suitable to the vacuum chamber that is used in the experiments. The pendulum mechanism consists of two parallel horizontal platforms and two pendulum arms. Double armed structure prevents changes in the direction thrust vector during the operation.[8] Also as the static balance of the system is increased with the double armed structure, positioning of the thruster on the upper platform does not have a significant effect on the measurement accuracy.[2] Mass of the thruster is balanced with the counterweights that are placed on the bottom platform, so that the effect of the thruster weight on the measurement is decreased. Pendulum parts are connected to each other with thin stainless steel flexural strips, therefore the mechanism is highly frictionless. Stiffness and measurement range of the system can be adjusted by changing these flexurals. Also, the measurement range and sensitivity can be adjusted by changing the counterweight mass.

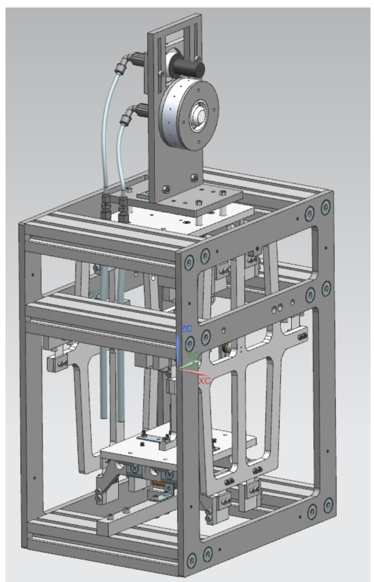

Figure 1. 3D drawing of the BUSTLab thrust stand with HK40 Hall Thruster

Displacement of the pendulum mechanism is measured with an LVDT displacement sensor, which has a sensitivity of 1.97 V/mm. It consists of a sensor and a core part. Sensor part of the LVDT is mounted on the bottom platform and core part is mounted on the upper platform (Fig. 2a). The pendulum structure has a very low natural frequency, so that the external perturbations are mechanically damped within the pendulum mechanism. A mechanically filtered output signal can be obtained by mounting the parts of the LVDT between upper and bottom parts of the pendulum mechanism. Also the sensor sensitivity is doubled, as both the sensor and core parts move with the pendulum.

The pendulum mechanism is highly frictionless, therefore a damper is required. For this purpose, an Eddy current damper is utilized. The damper mechanism consists of a copper plate that is mounted to the bottom platform and two electromagnets that are placed at each side of the copper plate. When current is applied to the electromagnets, an Eddy current is inducted in the copper plate, thus a damping force is applied to the pendulum.

As the thrusters generate heat during the operation, thrusters have to be thermally isolated from thrust

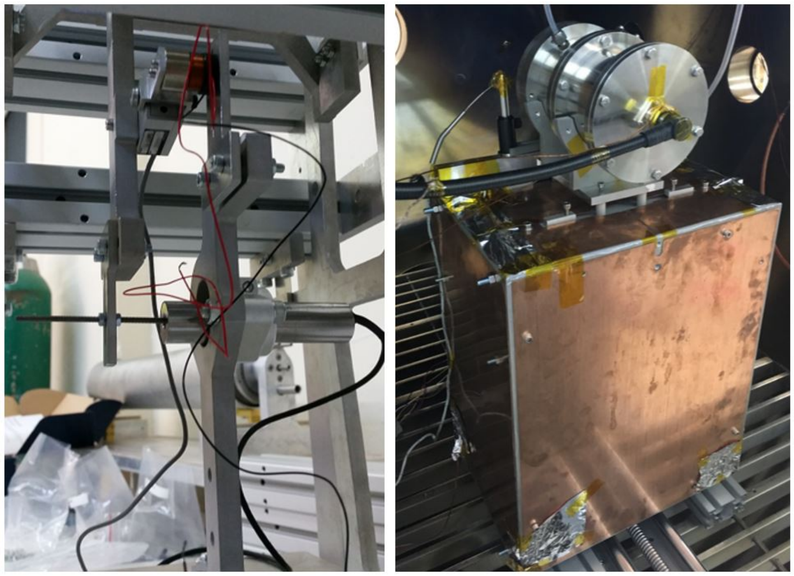

Figure 2. a) LVDT assembly b) Thrust stand with MET

stand. PEEK separators are placed between the thruster assembly and upper platform of the thrust stand. According to numerical analysis and experimental measurements, heat flux to the pendulum structure can be kept at very low levels. PEEK separators also provide electrical insulation, thus thruster assembly can be kept at a floating potential. Thrust stand is isolated from the plasma and electromagnetic waves inside the vacuum chamber with copper shields (Fig. 2b). All components and cables are insulated to minimize electromagnetic interference.

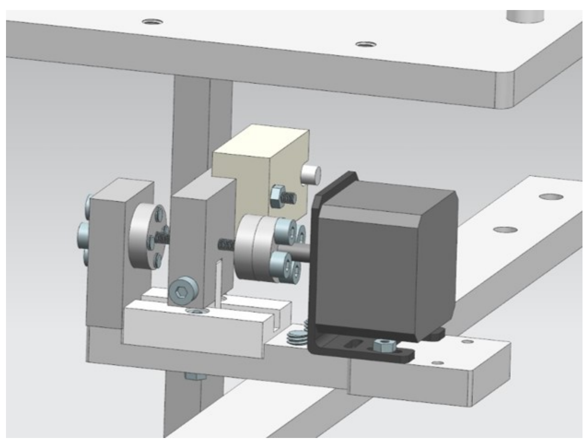

Figure 3. 3D drawing of the load cell and the linear stage

III. Calibration Process

Calibration is performed by using a pre-calibrated load cell with a sensitivity of 50 mV/mN. The load cell is attached to a linear stage (Fig. 3). Linear stage is actuated with a step motor with a resolution of 1.8 degree/step. The step motor rotates a fine adjustment screw, which has a thread length of 0.25 mm. Load cell is mounted on a platform, which slides along the screw. A Teflon rail constraints the rotational motion of the slider. Linear sensitivity of the linear stage is 1.25 μm/step. When actuated, the load cell is pushed to the upper platform and applies a dummy thrust force. Applied force is measured by the load cell, while thrust stand response is measured with LVDT. In situ calibration in the vacuum chamber before the tests can be performed. Temperature of the load cell is monitored during the calibration process, and necessary measurement tunings are applied.

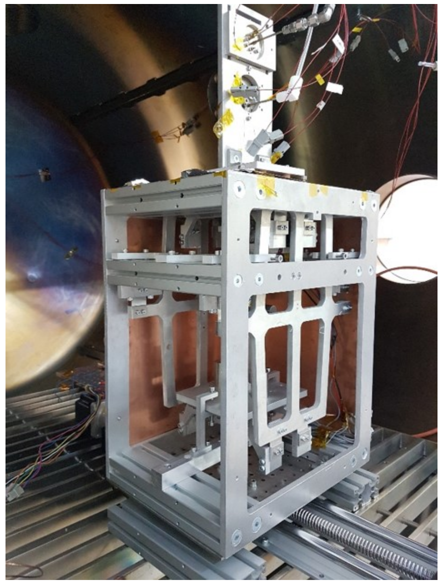

Figure 4. Thrust stand is mounted on a linear stage

IV. Experimental Setup

Thrust measurements are conducted inside the BUSTLab vacuum chamber, which is 1.5 m in diameter and 2.7 m in length[9]. Pressure inside the vacuum chamber is kept around 5×10^{-5} torr during the tests. Initial thrust measurements are conducted with two different thrusters that are developed at BUSTLab. These thrusters are HK Hall thruster[10–12] and BUSTLab microwave electrothermal thruster (MET)[13–17]. Power cables and propellant lines are connected to the thrusters in a waterfall configuration. With this configuration, low hysteresis levels are obtained. However, as the cables and pipes cause additional stiffness to the system, total stiffness of the system has to be adjusted by changing the counterweights according to the desired sensitivity and measurement range.

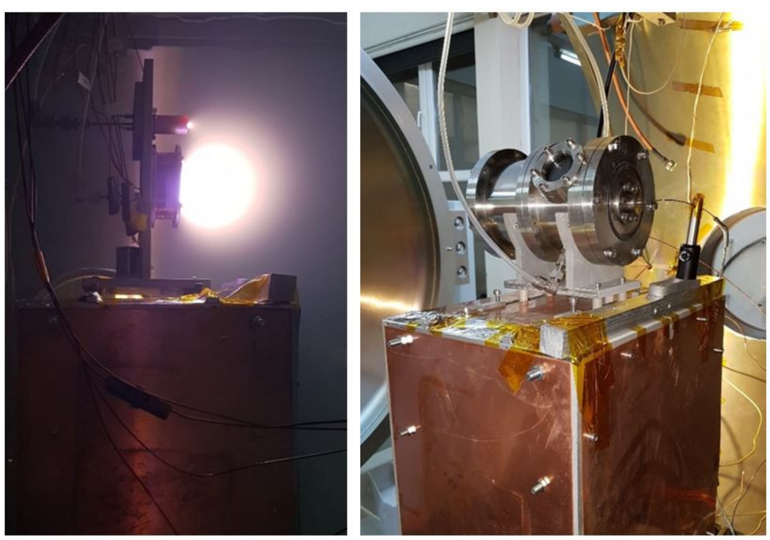

Figure 5. a) HK40 Hall thruster thrust measurement b) BUSTLab MET is mounted on thrust stand

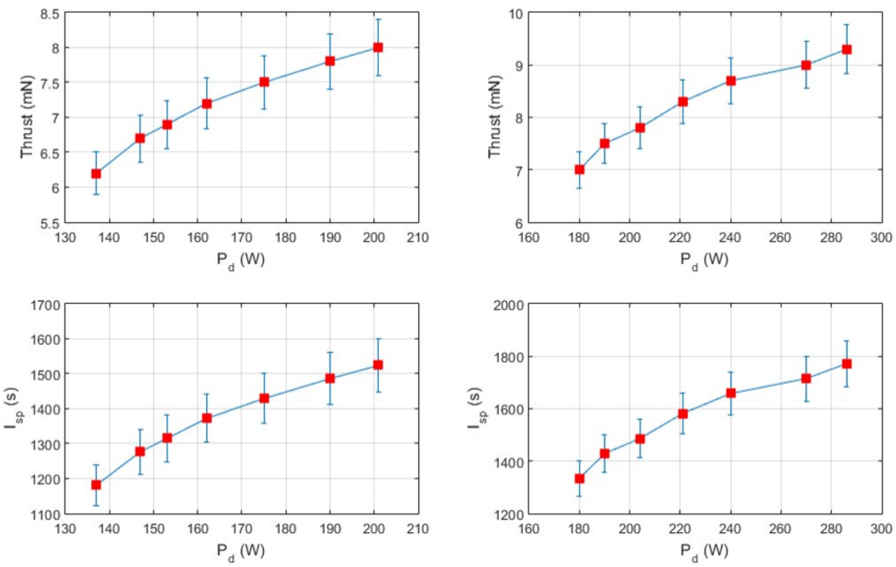

Figure 6. Thrust and specific impulse measurements of HK40 Hall thruster

During the tests different cables and pipes are used for different thruster types, therefore the pendulum position at zero thrust shifts. This shift is compensated with an additional linear stage (Fig. 4). Thrust stand is mounted on this linear stage, and can be moved forward or backward according to the null point drift. After a proper counterweight is placed and null point drifts are compensated with the linear stage, the calibration process begins. A dummy thrust force is applied through the load cell. Stiffness of the system is calculated from the load cell and LVDT measurements. After the calibration process thrust measurements begin. Calibration is repeated between measurement sequences to observe drifts during the operation. Uncertainty in the measurement is around 10% during the initial measurements.

V. Preliminary Results

Initial tests are conducted with the HK40 Hall thruster (Fig. 5a). HK40 is an SPT type Hall thruster with 40 mm discharge channel diameter. A prototype hollow cathode, developed at BUSTLab.[18,19], is used. This hollow cathode utilizes a LaB6 tube with 2 mm ID, 4 mm OD and 10 mm length. Argon is used during the tests. Thrust measurements are shown in Table 1 and Fig. 6.

Table 1. Operational parameters of HK40 Hall thruster

I_d (A)	V_d (V)	I_{in} (A)	I_{out} (A)	P_d (W)	T (mN)	I_{sp} (s)	η
1	137	0.75	1.00	137	6.2	1181	0.26
1	147	1.00	1.25	147	6.7	1277	0.29
1	153	1.25	1.50	153	6.9	1315	0.29
1	162	1.50	1.75	162	7.2	1372	0.30
1	175	1.75	2.00	175	7.5	1429	0.30
1	190	2.00	2.25	190	7.8	1486	0.30
1	201	2.25	2.50	201	8.0	1524	0.30

I_d (A)	V_d (V)	I_{in} (A)	I_{out} (A)	P_d (W)	T (mN)	I_{sp} (s)	η
1,2	150	0.75	1.00	180	7.0	1334	0.25
1,2	158	1.00	1.25	190	7.5	1429	0.28
1,2	170	1.25	1.50	204	7.8	1486	0.28
1,2	184	1.50	1.75	221	8.3	1582	0.29
1,2	200	1.75	2.00	240	8.7	1658	0.29
1,2	225	2.00	2.25	270	9.0	1715	0.28
1,2	238	2.25	2.50	286	9.3	1772	0.28

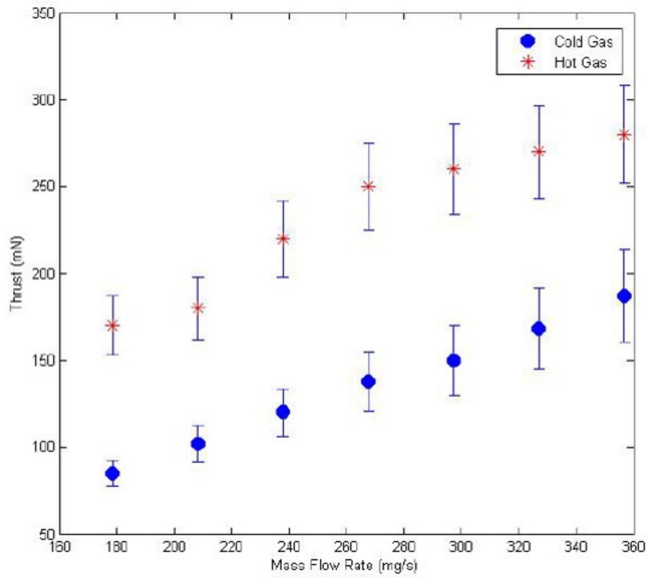

Figure 7. Thrust of MET for hot and cold gas operations

In a microwave electrothermal thruster (MET) microwaves are used to generate a free floating plasma inside a resonant cavity. Propellant is heated by using the floating plasma and then expelled through a nozzle. BUSTLab MET operates at 2.45 GHz. Argon is used as propellant. Tests are conducted for cold and hot gas operations (Fig. 5b). In cold gas operation no microwave power is transmitted to the thruster. During the tests it was observed that the temperature of the microwave coaxial power cable increases significantly, causing erreneous thrust readings. In order to overcome this problem, thrust measurements were conducted by comparing the thrust levels before and immediately after the thruster is turned off. Thruster power and mass flow can be turned off very quickly, therefore thermal drifts during the measurement process can be kept at minimum.[15] Test results are shown in Table 2 and Fig. 7.

Table 2. Operational parameters of MET for hot and cold gas operations

	Cold Gas		Hot Gas	
mfr [mg/s]	p_c [torr]	τ [mN]	p_c [torr]	τ [mN]
178	252	85	405	170
208	300	102	480	180
237	347	120	570	220
267	393	138	634	250
297	440	150	700	260
327	486	168	760	270
356	534	187	830	280

VI. Conclusion

A thrust stand for thrust measurements at mili-Newton levels is designed and built. Thrust stand design enables adjustments for different thrust measurement ranges, thus electric propulsion systems at various thrust levels can be tested with high accuracy. The pendulum mechanism provides mechanically filtered output signal. In situ calibration can be performed in high vacuum by using a load cell. Preliminary thrust measurements are conducted for HK40 Hall thruster and BUSTLab microwave electrothermal thruster.

Acknowledgments

The authors acknowledge the financial support by Bogazici University Research Fund Grant Number BAP-11482. The authors would like to thank Prof. Huseyin Kurt for his contributions to this study.

References

[1]Martinez-Sanchez, M. and Pollard, J.E., Spacecraft Electric Propulsion-An Overview, *Journal of Propulsion and Power*, Vol. 14, No. 5, 1998, pp. 688699.

[2]Pancotti, A., Haag, T., King, S., and Walker, M., "Recommended Practices in Thrust Measurements", *33rd International Electric Propulsion Conference*, Washington, DC, USA, October 2013, IEPC-2013-440.

[3]Neumann, A., Sinskes, J., and Harmann, H. P., The 250mN Thrust Balance for the DLR Goettingen EP Test Facility", *33rd International Electric Propulsion Conference*, Washington, DC, USA, October 2013, IEPC-2013-211.

[4]Xu, K. G. and Walker, M. L. R., High-power, null-type, inverted pendulum thrust stand", *Review of Scientic Instruments*, Vol. 80, No. 5, 2009.

[5]Harmann, H.P., Dartsch, H., and Werner, E., Low Drift Thrust Balance with High Resolution", *34th International Electric Propulsion Conference*, Hyogo-Kobe, Japan, July 2015, IEPC-2015-257.

[6]Hey, F. G., Keller, A., Papendorf, D., Braxmaier, C., Tajmar, M., Johann, U., and Weise, D., Development of a Highly Precise Micro-Newton Thrust Balance", *33rd International Electric Propulsion Conference*, Washington, DC, USA, October 2013, IEPC-2013-275.

[7]Packan, D., Bonnet, J., and Rocca, S., Thrust Measurements with the ONERA Micro-Newton Balance", *31st International Electric Propulsion Conference*, Ann Arbor, MI, USA, September 2009, IEPC-2009-185.

[8]Tartler, B. and Martinez-Sanchez, M. "Construction and Performance of an Inverted Pendulum Thrust Balance," Master's thesis, MIT, May 2010.

[9]Korkmaz, O., Jahanbakhsh, S., Celik, M., and Kurt, H., Space Propulsion Research Vacuum Facility of the Bogazici University Space Technologies Laboratory, *7th International Conference on Recent Advances in Space Technologies (RAST)*, Istanbul, Turkey, June 2015.

[10]Turan, N., Experimental Investigation of the Effects of Cathode Position on HK40 Hall Effect Thruster Performance and Cathode Coupling, M.S. Thesis, Bogazici University, Istanbul, Turkey, December 2016.

[11]Turan, N., Kokal, U., Kurt, H. and Celik, M., Experimental Study of the Effects of the Cathode Position and the Electrical Circuit Con

guration on the Operation of HK40 Hall Thruster and BUSTLab Hollow Cathode, *52nd Joint Propulsion Conference*, Salt Lake City, UT, July 2016, also AIAA-2016-4834.

[12]Turan, N., Kokal, U. and Celik, M., Experimental Investigation of the Effects of Cathode Current on HK40 Hall Thruster Operation, *5th International Conference on Space Propulsion*, Rome, Italy, May 2016, SP2016-3125333.

[13]Yildiz, M. S. and Celik, M., Global Energy Transfer Model of Microwave Induced Plasma in a Microwave Electrothermal Thruster, *34th International Electric Propulsion Conference*, Kobe, Japon, July 2015, IEPC-2015-266.

[14]Yildiz, M. S. and Celik, M., Experimental Performance Analysis of the BUSTLab Microwave Electrothermal Thruster, *52nd Joint Propulsion Conference*, Salt Lake City, UT, July 2016, AIAA-2015-3926.

[15]Yildiz, M.S., Kokal, U. and Celik, M., Preliminary Thrust Measurement Results of the BUSTLab Microwave Electrothermal Thruster, *53rd Joint Propulsion Conference*, Atlanta, GA, July 2017, also AIAA-2017-4725.

[16]Yildiz, M.S. and Celik, M. Numerical Investigation of the Electric Field Distribution and the Power Deposition in the Resonant Cavity of a Microwave Electrothermal Thruster, *AIP Advances*, Vol. 7, No. 4, 045021, April 2017.

[17]Yildiz, M.S. and Celik, M. Global Energy Transfer Model of a Microwave Electrothermal Thruster Operating with Helium Propellant at 2.45 GHz Frequency, *IEEE Transactions on Plasma Science*, Vol. 45, No. 8, pp. 2314-2322, August 2017.

[18]Kokal, U., Turan, N. and Celik, M., Thermal Analysis and Testing of Different Designs of Lanthanum Hexaboride Hollow Cathodes, *8th International Conference on Recent Advances in Space Technologies (RAST)*, June 2017.

[19]Kurt, H., Turan, N., Kokal, U. and Celik, M., Note: Coaxial-heater Hollow Cathode, *Review of Scientific Instruments*, Vol. 88, No. 6, pg. 066103, 2017.