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

Ugur Kokal*, Murat Celik
Department of Mechanical Engineering
Bogazici University
Istanbul, Turkey
*Corresponding Author: ugur.kokal@boun.edu.tr

***Abstract*—Electric propulsion systems operate with high efficiency, however they generate low thrust. Therefore pendulum based sensitive measurement systems are used for thrust measurements of electric propulsion systems. In this study, a thrust stand is developed and built for the thrust measurements of electric thrusters. The thrust stand that is developed is based on inverted pendulum configuration, and can measure thrust forces at mili-Newton levels with a resolution of ~100 micro-Newton levels. Measurement range can be changed according to the thruster, by adjusting the components of the thrust stand.**

Keywords— electric propulsion, thrust measurement, thrust stand.

I. INTRODUCTION

Space propulsion systems are used for maneuvers of the spacecraft in orbit or during deep space missions. Most commonly used space propulsion systems are chemical propulsion systems and electric propulsion systems. Chemical propulsion systems utilize the chemical energy of the propellant, while electric propulsion systems converts the electrical energy that is obtained from solar panels or other power sources into the kinetic energy of the propellant [1]. Chemical systems provides higher thrust than electric propulsion systems, however they operate at lower efficiencies and at lower specific impulses. Therefore, while the chemical propulsion systems are suitable for launch vehicles and maneuvers that requires fast burns, electric propulsion systems can provide higher delta-V with less propellant, and are more suitable for long duration missions, such as deep space missions and station keeping applications [2].

Electric propulsion systems have been developed since 1960’s [3]. These systems can be grouped into three main categories: electrostatic, electromagnetic and electrothermal propulsion systems. Each category has different thrust and specific impulse levels. As the achievable thrust levels of electric propulsion systems are much lower than those of chemical systems, classical 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 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. In order to achieve this goal, pendulum based thrust stands are developed. In a pendulum mechanism, the thrust vector and the gravity vector can be separated, thus very low thrusts can be measured without being affected by the weight of the thruster [4].

Different pendulum configurations are developed for thrust measurements of the electric propulsion systems. These are hanging pendulum, inverted pendulum and torsional pendulum [5]. 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 a torsional pendulum, the thruster and a counterweight are placed on a horizontal pendulum arm. Each configuration has different advantages and disadvantages.

Different thrust stand designs have been built in research centers for thrust measurements of electric propulsion systems. An important example is the thrust stand developed at NASA Glenn Research Center, which utilizes an inverted pendulum configuration [6]. The structure of the thrust stand consists of two parallel pendulum arms as shown in Fig. 1., and is kept at stationary position by an active control system.

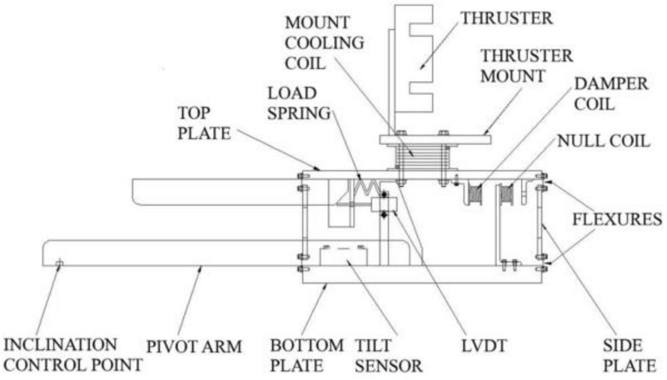

Fig. 1. Schematic diagram of NASA Glenn Research Center thrust stand [4]

Another thrust stand that is based on inverted pendulum configuration is developed by DLR Goettingen Electric Propulsion Test Facility [7]. 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 [8-9]. Both thrust stands are designed for thrust measurements at micro-Newton levels.

II. EXPERIMENTAL SETUP AND DESIGN CONSTRAINTS

Thrust stand is designed to be used in thrust measurement tests of the electric propulsion systems. Hence experimental setup and thruster parameters, such as thruster mass and expected thrust levels are important parameters for the thrust stand design. As the thrusters are designed to operate in the space, ground tests should be conducted in high vacuum environment. Therefore, the tests will be conducted inside the BUSTLab (Bogazici University Space Technologies Laboratory) vacuum chamber, which is 1.5 m in diameter and 2.7 m in length. Chamber walls may have an effect on the thruster because of the interference with the plasma ejected from the thruster, therefore during measurements the thruster should be positioned far from the chamber walls and near the center of the vacuum chamber. Therefore, thrust stand dimensions are determined according to the dimensions of the vacuum chamber. During the tests, the pressure inside the vacuum chamber is kept around 5×10^{-5} torr, therefore the thrust stand is built from vacuum safe components, and thus outgassing is minimized.

The thrust stand is used primarily for the thrust measurements of the thrusters that are developed at BUSTLab. These thrusters include a Hall Effect thruster, a Cusped Field Hall Thruster (CFHT), an RF ion thruster and a microwave electrothermal thruster (MET). Hall Effect thruster, CFHT and RF ion thrusters generate thrust forces up to 20 mN theoretically [10-11]. However theoretical thrust level of MET can be as high as 300 mN [12]. Measurement range of the thrust stand should cover all these levels. Also, in order to achieve optimum resolution at each case, the thrust stand is designed to be adjustable for different measurement ranges. As the thrust levels are very low and the pendulum mechanism is very sensitive to achieve high resolution, any external perturbation may affect the result. The vibrations caused by the cyropumps are damped with the help of the pendulum mechanism, due to the inherent low natural frequency characteristic of the pendulum mechanism. During the operation, thrusters generate heat, which is removed from the thrusters via conduction and radiation. Thermal conduction to the thrust stand may affect the results; consequently thermal control of the thrust stand is crucial. Also the thrust stand should be protected from the plasma in the vacuum chamber.

III. THRUST STAND DESIGN

Considering the design constraints and requirements, inverted pendulum structure is chosen for the thrust stand design. Inverted pendulum configuration provides high sensitivity with a compact structure. The design consists of a double armed pendulum, which consists of two parallel vertical pendulum arms as can be seen in Fig. 2. Double armed pendulum structure prevents changes in the direction of the thrust vector [13]. Besides, as the static balance of the system is increased, the position of the thruster does not have a significant effect on the measurement accuracy [4]. In order to increase the stability and to avoid the effect of the thruster weight on the measurements, a counterweight is added to the design. The thruster is mounted on the upper platform of the pendulum, and the counterweight is mounted on the bottom platform (Fig. 3.). By stabilizing the system, sensitivity of the thrust stand to the vibrations in the vacuum tank is reduced further [7].

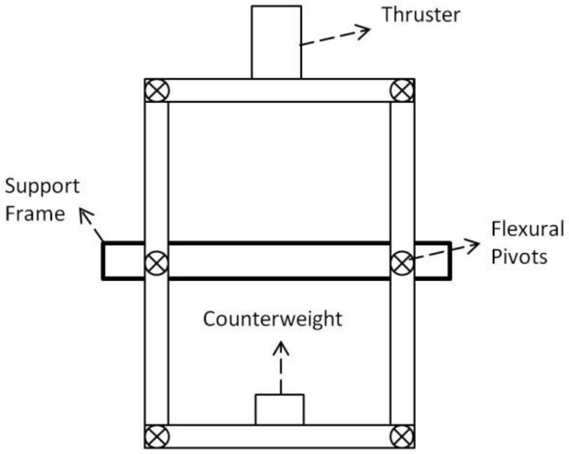

Fig. 2. Counterbalanced inverted pendulum concept

Pendulum arms and horizontal platforms are connected by frictionless flexural thin strips. Also whole pendulum structure is connected to the outer frame with additional flexures. The pendulum assembly has one degree of freedom and can be deflected by an applied thrust. The thin flexural strips determine the stiffness of the system, thus they determine the measurement range and sensitivity, which can be adjusted by changing these flexures. Flexural thin strips are made of 304 type stainless steel. Pendulum arms and the horizontal platforms are made of 5083 grade aluminum.

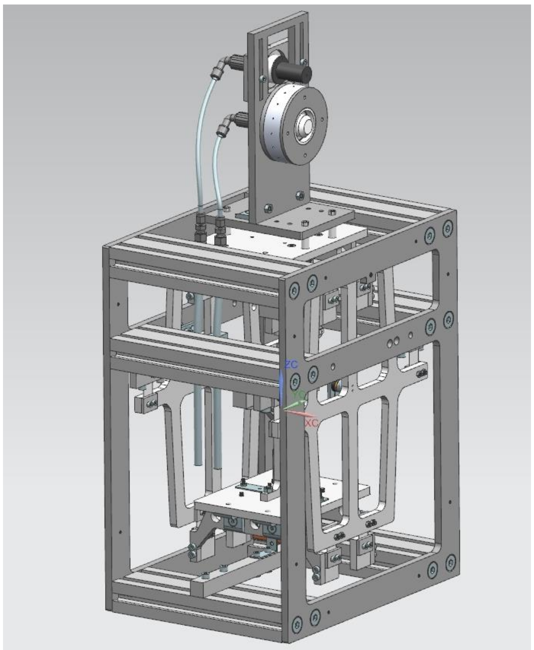

Fig. 3. 3D drawing of thrust stand with Hall Effect Thruster

IV. MODELLING AND ANALYSIS OF THRUST STAND

Thrust stand design includes many design variables, such as pendulum arm length and flexural stiffness. These variables should be optimized for high sensitivity at the desired measurement range. In order to optimize the thrust stand components, each component of the thrust stand is analyzed. Flexural stiffness, which is the bending stiffness of the thin strips, is the primary design variable that determines the measurement range and sensitivity. Therefore flexural stiffness of the thin strips is analyzed analytically and then numerically. Another important design parameter is the pendulum arm length. In order to determine proper dimensions, a comprehensive analysis for thrust stand response is conducted. According to these analyses, appropriate sensors and actuators are determined. Design parameters are then optimized for these.

A. Analytical Model of Flexures

Bending is caused by the applied thrust force. Both ends of the strips are attached to neighboring pendulum parts, therefore these edges are not free edges. As the angle of horizontal platforms and outer frame parts are fixed, end edges of the strips, which are attached to these parts have fixed displacement angle, which is zero. Other edges of the strips have a displacement angle that is equal to the angle of the pendulum arm. Because of the geometric constraints, all strips have same deformation shape, which means that they are affected by the same force and moment. Therefore all the strips can be represented as a single strip connecting the pendulum arm to the fixed base as shown in Fig. 4.

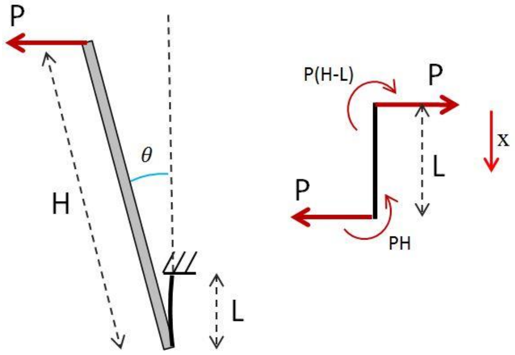

Fig. 4. Simplification of the pendulum structure as one strip and a pendulum arm (left), free body diagram of the strip (right)

In Fig. 4. P represents the applied thrust by the thruster, H is the pendulum arm length, L is the length of the strip and θ is the deformation angle. After solving the Euler-Bernoulli beam equation for the pendulum mechanism, the thrust stand response can be found:

$$k\theta = PH \tag{1}$$

Where k is the total bending stiffness of the strips, which is equal to EI/L, where E is the modulus of elasticity, and I is the area moment of inertia.

B. Numerical Analysis of Thrust Stand

Numerical analyses are conducted by using the structural mechanics module of COMSOL (Fig. 5.). Pendulum arms and horizontal plates have much higher rigidity compared to the flexible thin strips; therefore these plates are modeled with solid mechanics physics of structural mechanics module. The thin strips are modeled with shell physics. In shell module of COMSOL, the thin strips are evaluated as 2D domains, so that the number of nodes and the computational time is reduced.

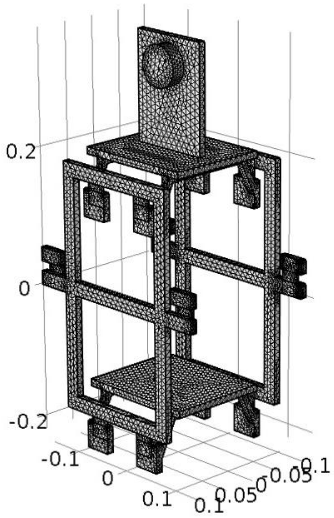

Fig. 5. Computational grid for finite element modeling of thrust stand

From the numerical model, stress levels and deflection at the flexures due to the bending are found as shown in Fig. 6. Thrust stand response is highly linear with respect to the applied force. Also, effect of flexure thickness is investigated.

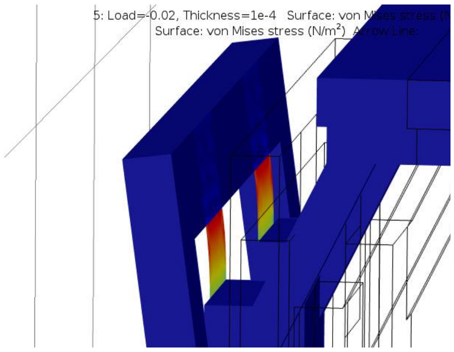

Fig. 6. Bending of the flexures between the pendulum arms and upper platform

It has seen that the deflection of the pendulum is proportional to the third power of the flexure thickness. Value of the flexure thickness is determined to be 0.1 mm for 20 mN thrust measurement range as can be seen in Fig. 7, while 0.25 mm thickness is suitable for 320 mN thrust measurement. Transient response of the thrust stand is also investigated. Natural frequency of the thrust stand is an important parameter for resonance avoidance and vibration isolation. The dominant frequency of the vibrations in the vacuum chamber is 1 Hz, which is the operation frequency of the cyropumps. The thrust stand should have a natural frequency much lower than this value. According to the analysis results, the natural frequency of the thrust stand is around 0.25 Hz (Fig. 8).

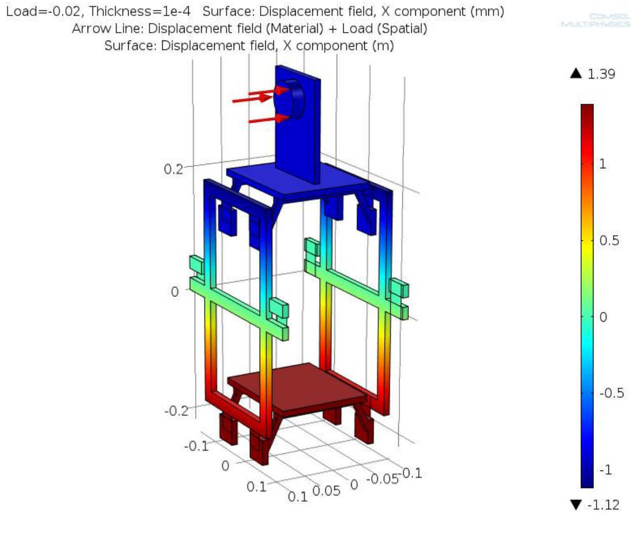

Fig. 7. Thrust stand response for 20 mN thrust with the flexure thickness of 0.1 mm

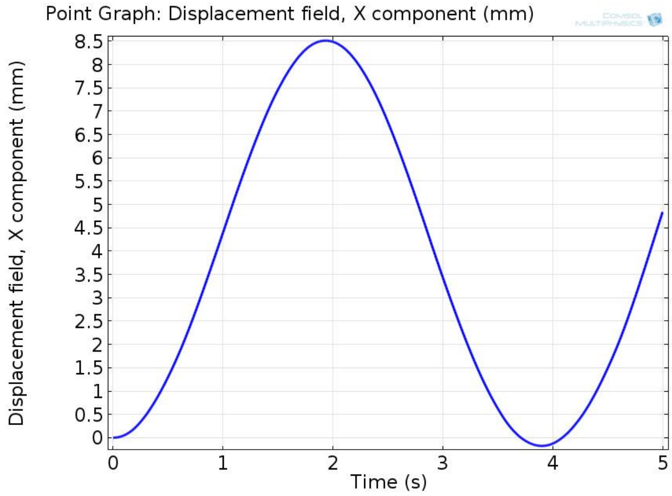

Fig. 8. Transient response of the thrust stand for 20 mN thrust with the flexure thickness of 0.1 mm

V. COMPONENTS OF THE THRUST STAND

A. Displacement Sensor

The deflection of the thrust stand is measured with a displacement sensor. As displacement sensor, an LVDT (Linear Variable Differential Transformer) is utilized. LVDT sensors convert the linear displacement into a proportional electrical signal. The sensor that is used in the thrust stand has a sensitivity of 1.97 V/mm. It consists of a moving core part and a coil assembly, and operates without any contact. The core and coil parts of the LVDT are placed between the top and bottom platforms of the pendulum as can be seen in Fig. 9. As the pendulum structure acts as a vibration isolation element, the displacement signal is filtered from external vibrations. Also by placing the LVDT components between the both ends of the pendulum, sensitivity of the sensor is doubled.

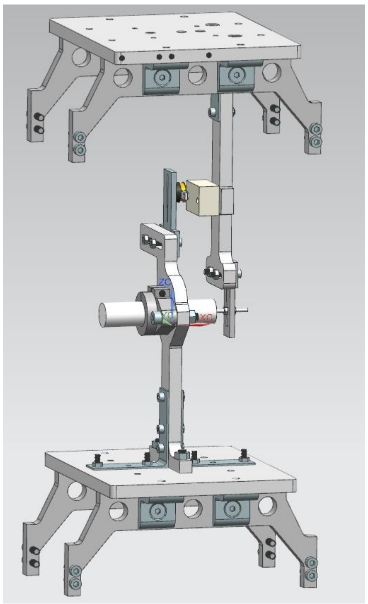

Fig. 9. Sensor assembly of the thrust stand. Pendulum arms are not shown here.

B. Calibration System

In order to calibrate the system before tests, two different designs are proposed. In both designs a load cell is used for the calibration. Load cells convert the applied force to an electrical signal by utilizing strain gauges. A load cell with the sensitivity of 50 mV/mN is utilized in the thrust stand. Load cell is calibrated separately before the tests by applying known forces with calibration weights.

Fig. 10. Sensor assembly: LVDT is in the middle, voice coil and load cell is in the upper part

In the first calibration system, a voice coil and a load cell assembly is utilized (Fig. 10). Voice coils consist of a copper wire solenoid and a permanent magnet. With a voice coil, a force which is linearly dependent on the applied current can be generated without any contact. The voice coil that is used in the thrust stand has a sensitivity of 290 mN/A. The magnet part of the voice coil is attached to the upper platform through the load cell, which measures the applied force by the voice coil. Coil part of the voice coil is attached to the bottom platform. During the calibration process, a force is applied by the voice coil and a deflection in the pendulum assembly is generated. Applied force is measured with the load cell, while the deflection is measured with the displacement sensor. From the values of the deflection and the applied force, stiffness of the thrust stand is calculated. In-situ calibration can be performed inside the vacuum chamber automatically. The main disadvantage of this calibration system is the difficulties of the connection of the load cell and the voice coil. Weight of the voice coil causes some measurement errors and undesired vibrations.

In the second design for the calibration system, the load cell is attached to a motorized linear stage (Fig. 11). The linear stage is actuated with a step motor, which has a resolution of 1.8 degree/step. A fine adjustment screw with thread length of 0.25 mm is attached to the step motor. Load cell is attached to a platform, which has fine internal threads. The platform moves along the screw, when the screw is actuated by the step motor. Rotational motion of the platform is avoided with a Teflon rail. A linear sensitivity of 1.25 µm/step can be achieved with this stage. In the low thrust measurement configuration with 20 mN thrust range, a calibration resolution around 20 µN can be achieved. With this second calibration design, a rigid calibration system is obtained.

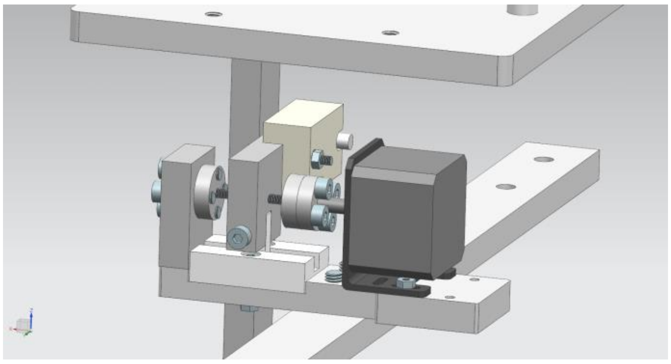

Fig. 11. 3D drawing of linear stage assembly. When actuated, load cell is pushed against the vertical bar that is attached to the upper platform.

C. Damping System

As the pendulum assembly of the thrust stand is designed to be frictionless, the movements of the pendulum are not damped for a long time. Also, external vibrations in the vacuum chamber may cause undesired oscillations in the system. In order to damp these undesired oscillations, an eddy current damping system is used. Damping system consists of a copper plate, which is attached under the bottom platform, and two electromagnets placed at each side of the copper plate without any contact (Fig. 12). A magnetic field through the copper plate is generated by applying current to the electromagnets. When the plate moves with the pendulum, an eddy current is induced in the plate, thus a damping force is generated [14]. Damping ratio of the damping system can be adjusted by applying different currents to the electromagnets.

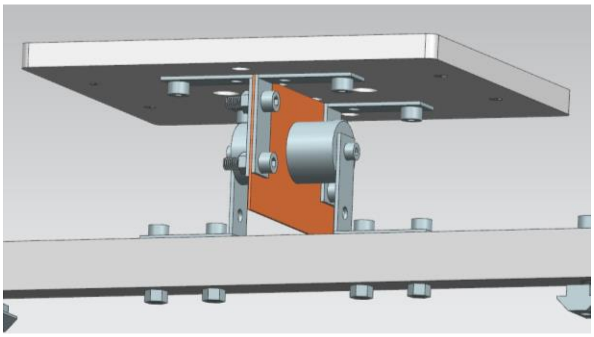

Fig. 12. Damping assembly with the electromagnets and copper plate. Only the bottom plate of the pendulum structure is shown here.

VI. THERMAL ANALYSIS OF THRUST STAND

Due to the design of the thrust stand, temperature changes may affect the measurement accuracy. Also high temperatures may harm the electronic equipment. Therefore thrust stand have to be thermally insulated from the thruster, which is the main heat generating element during the tests. Thrust stand is insulated from the thrusters via PEEK separator parts. PEEK parts also provide electrical insulation. Heat transfer analysis was conducted for the maximum heat generation case, which occurs during the heating process of the hollow cathode that is utilized as the neutralizer. Thermal analysis of hollow cathode is conducted separately. According to the analysis results, thrust stand temperature can be kept at low temperatures (Fig. 13). In order to protect the thrust stand from the plasma and electromagnetic waves inside the vacuum chamber, the whole structure is covered with metal shields.

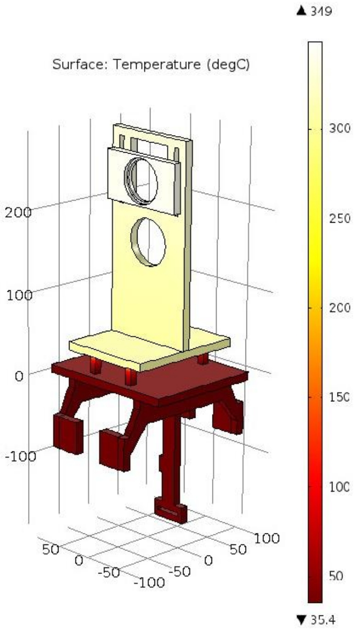

Fig. 13. Thermal analysis of the upper part of the thrust stand for the cathode heating process.

VII. MANUFACTUING AND TEST PROCEDURE

The plates of the pendulum structure are manufactured via water jet cutting. After the cutting process, hole drilling, taping and surface finishing processes are performed. After the completion of the manufacturing and assembly processes (Fig. 14), thrust measurement tests will be conducted. Measurement procedure begins with the calibration. After determining the stiffness of the thrust stand during the calibration, the thruster operation is initiated. Measurements are performed in two modes. In passive mode, the pendulum mechanism deflects freely and the deflection is measured with the displacement sensor. This mode requires no active control. In active mode, a closed control loop keeps the pendulum at stationary position by actuating the step motor or voice coil. Displacement sensor provides position feedback. Thrust force is measured with the load cell. In this mode effects of components such as cables and pipes are avoided.

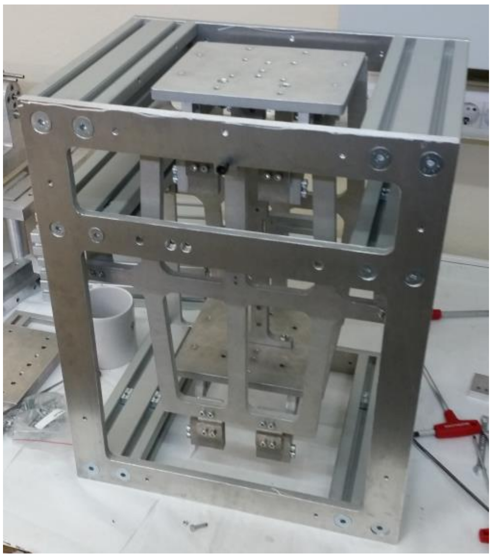

Fig. 14. Thrust stand after the assembly.

VIII. CONCLUSION

In this study, a thrust stand for thrust measurements at mili-Newton levels is developed and built. Thrust stand is analyzed theoreticaly and design parameters are optimized for maximum sensitivity. The design enables adjustments for different thrust measurement ranges, thus electric propulsion systems at various thrust levels can be tested with high accuracy.

As a future work, the thrusters that are developed at BUSTLab will be tested with the thrust stand and their operational parameters will be obtained. Beside the thrust measurements, efficiency and specific impulse levels can also be calculated from the measured thrust forces.

Some modifications for the thrust stand are also proposed. A vibration isolation system between the vacuum chamber and the thrust stand may decrease the noise that is caused by the vibrations at the vacuum chamber. Also an active cooling system may prevent measurement errors caused by temperature drifts.

Acknowledgment

The authors would like to thank Turkish Scientific and Technological Research Council (TUBITAK) for their partial support to this work under project number 214M572. The authors also acknowledge the financial support from Bogazici University Scientific Projects Office (BAP) under project number BAP-11482. The authors would like to thank Huseyin Kurt for his contributions to this study.

References

[1] Erichsen, P., “Performance Evaluation of Spacecraft Propulsion Systems in Relation to Mission Impulse Requirements”, Proceedings of the Second European Spacecraft Propulsion Conference, Noordwijk, Netherlands, 1997.

[2] Jahn, R. G. and Choueiri, E. Y., “Electric Propulsion", Encyclopedia of Physical Science and Technology, No. 3589, 2002.

[3] Martinez-Sanchez, M. and Pollard, J.E., “Spacecraft Electric Propulsion-An Overview,” Journal of Propulsion and Power, Vol. 14, No. 5, 1998, pp. 688–699.

[4] 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.

[5] 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.

[6] 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.

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

[8] 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.

[9] 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.

[10] Turan, N., Kokal, U., Kurt, H. and Celik, M., “Experimental Study of the Effects of the Cathode Position and the Electrical Circuit Configuration on the Operation of HK40 Hall Thruster and BUSTLab Hollow Cathode," 52nd Joint Propulsion Conference, Salt Lake City, UT, USA, July 2016, AIAA-2016-4834.

[11] Turan, N., Kokal, U. and Celik, M., “Experimental Investigation of the Effects of Cathode Current on HK40 Hall Thruster Operation," 5th Space Propulsion Conference, Rome, Italy, May 2016, also SP2016_ 3125333.

[12] Yildiz, M.S. and Celik, M., “Experimental Performance Analysis of the BUSTLab Microwave Electrothermal Thruster," 52nd Joint Propulsion Conference, Salt Lake City, UT, USA, July 2016, AIAA-2016-4949.

[13] Tartler, B. and Martinez-Sanchez, M., “Construction and Performance of an Inverted Pendulum Thrust Balance”, Master's Thesis, MIT, May 2010.

[14] Cunningham, R. E., “Passive Eddy-Current Damping as a Means of Vibration Control in Cyrogenic Turbomachinery", NASA Technical Paper, No. 2562, 1986.