JOURNAL OF CURRENT RESEARCH IN SCIENCE
ISSN 2322-5009
CODEN (USA): JCRSDJ
Available at www.jcrs010.com

JCRS
4 (3), 2016: 54-59

Six-axis stand for measuring thrust vector of space propulsion systems

Alireza Basohbat Novinzadeh, Majid Rahimi Delvand*

Department of Aerospace Engineering, Khajeh Nasireddin Toosi University, Tehran, Iran
** Corresponding Author email: Majidrahimi@mail.kntu.ac.ir*

K E Y W O R D S: six-axis stand, space propulsion system, spacecraft calibration.

ABSTRACT: The propulsion subsystem plays a key role in the majority of space systems. This key role results in very accurate and free of error performance of propulsion subsystem, which customers are always expecting. With the increasing use of these systems in recent years, it is necessary to design and develop a domestic stand for such a precise calibration. A stand which could measure the magnitude of produced thrust, and also determines the force (thrust) vector. This paper presents the creative design of a domestic stand, which aims to accurately measure the thrust vector of space propulsion systems, so that it specifies the necessary actions for its implementation.

Introduction

Design and construction of complex and intelligent systems, demands the use of methods to measure the confidence level and the proper functioning of these systems. Ways with the least possible time and with the imposition of the lowest costs, which measuring the performance of the system before producing the final sample, enable us to review the design and make the implementation of the necessary changes. According Rahimi et al. (2013) Space projects are among the most expensive and sophisticated and most precise projects which are developing rapidly. The unique characteristics of such systems and also limited access to them (while operating in orbit), necessitates the highest possible levels of designing and manufacturing for them (1). It's obvious that exact performance of each complex set is a function of precise performance of each subsystems of that system. Failure of complex systems is generally caused by two reasons:
System defect in response to expected performing needs.
Defect in one (or more) specific subsystems in response to expected performing needs

First reason generally occurs when a senior designer, doesn't design the project careful enough and neglect key points in collecting system performance features, by total performance tests (i.e. hardware-in-the-loop tests). For example a complicated system which consists of several intact subsystems, because of coupling performance of two random subsystems, shows a rare error and fails while performs. Such objections could be avoided by real-time simulations. The common solution is to use the general methods and standards of system engineering. These approaches are using a predefined hierarchy, and present a safe and precise and tested design.

The second reason which is the failure of one (or more) specific subsystems in proper response to expected performance needs occurs when the chosen subsystem by the designer, has a performance error. Generally this type of error is caused by not determining the tolerance in such systems. For instance one these common subsystems in satellites are propulsion subsystem. This subsystem is usually used in orbit and attitude control of satellites. Though exhaust nozzles of thrust gas are built carefully, in addition to desired thrust force (axial force) some sidelong forces are produced too. These unwanted sidelong forces create a new thrust vector (undesirable force). This new force creates new unwanted changes in whole complex. Knowing about the error rate of these subsystems, may contribute to design an appropriate controller for the satellite and avoids the failure (or unpredicted actions) of whole satellite caused by undesired performance of thrust subsystems. The solution for such problems is the individual (separated) test for subsystems. Nowadays these tests are Non-removable part of the manufacturing process of subsystems which are used in complicated systems.

According to rapid use of cold gas thruster in space industries, the need for precise performance of these thrusters, and considering above notes about the importance of utilized individual tests in subsystems, developing a domestic six-axis stand is required. In order to achieve this aim, first the available technical knowledge in the field will be reviewed and then by investigating advantages and disadvantages of current designs, an innovative design of a domestic six-axis stand will be presented.

The problem

Considering the need of space industries for calibration of propulsion systems and considering inefficiency in current assemblies, designing a domestic six-axis stand seems to be necessary. This stand should be able to calculate the

thrust force produced by space thrusters in vector method. Which means it determines 6 main components of produced force vector. These parameters are:
3 location components (The point which the thrust vector exerted on (x,y,z))
3 magnitude components (Magnitude of forces in the 3 main axis (F_x ،F_y ،F_z))

Measuring of these 6 components should be done in a controlled way by considering the functional limitations of space propulsion systems. Most important limitations are listed below:
Stand should be able to measure the (δ) distance of thrust vector from the main axis and to determine (α) thrust vector deviation angle (in fact be able to measure the lateral forces (Fig. 1)).
The designed stand should be able to measure the thrust vector in a short time (in hundreds of seconds). Because space thrusters, normally produce impact forces, i.e. the thrusting forced produced by them doesn't last long and action of this force is terminated in milliseconds.

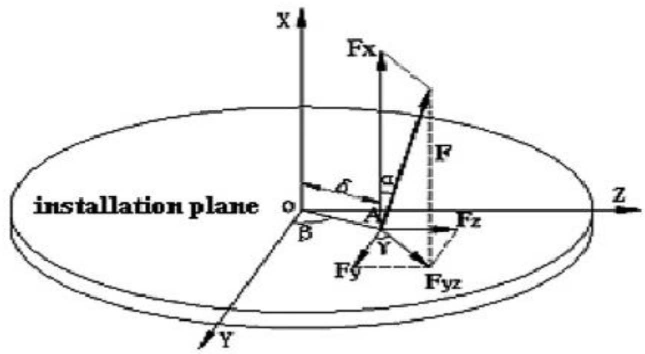


Figure 1. Eccentricity components schematic of the thruster (2)

Literature review

After reviewing published resources, it was found out that in context of testing space thrusters (especially cold gas thrusters) there is no astonishing stand which could measure all components of thrust vector of thrusters and majority of current stands can only measure the magnitude of thrust force in the longitudinal axis of the thruster.

Facing this need was an encourager to investigate the thrust vector measurement stands. Two of these stands are assessed.

First sample. Single-axis stand for measuring cold gas thrusters, thrust vector (produced by Naval institute).

According Lugini et al. (2009) this thrust measuring stand is developed by the cooperation of experts in Toulouse in France and Naval in U.S for cold gas thrusters. This stand is presented as Fig. 2.

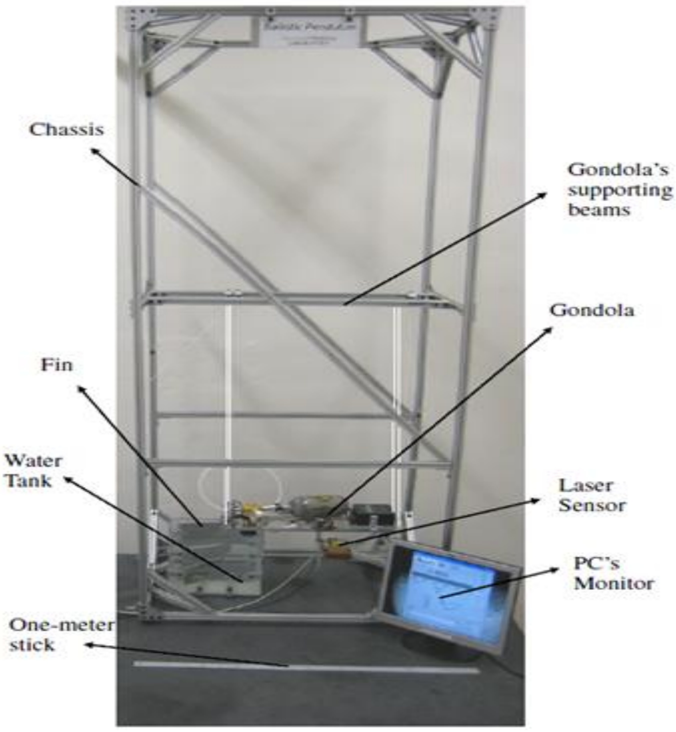


Figure 2. Ballistic pendulum stand (4)

Exterior structure holds a floating gondola by four strings. This gondola which can swing freely holds the cold gas thruster system and its nozzle. Under the holding gondola (near the center of mass) a plate (Perpendicular to the gondola) is installed and considered as the target of laser sensor. Calculating the thrust force is done by a laser sensor. This sensor which is installed on the main frame provides the controlling system of stand with necessary data for calculating the thrust force by measuring the displacement of the gondola of the thruster.

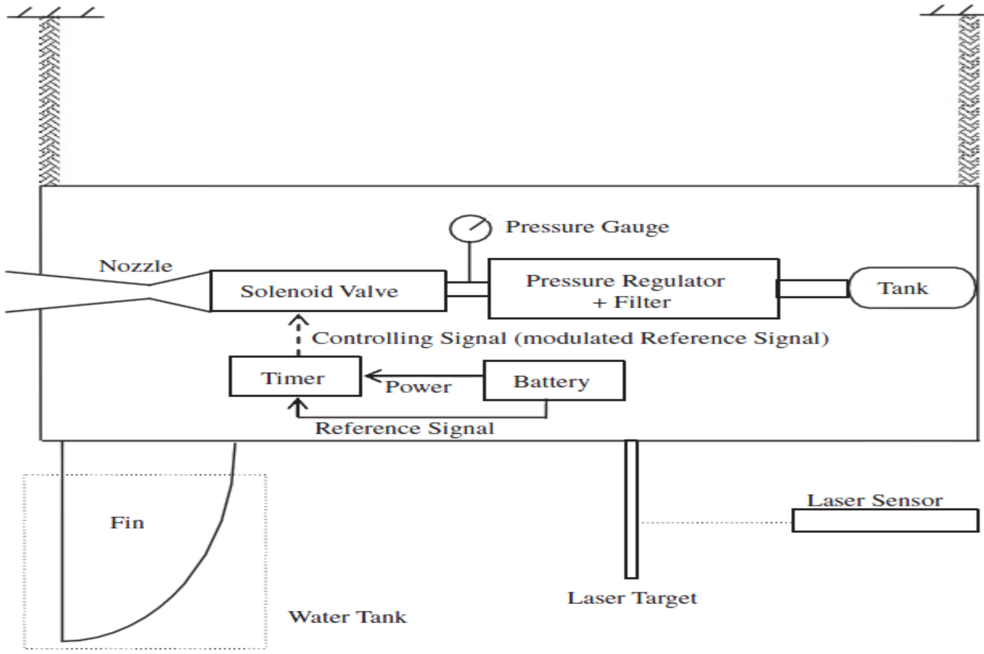


Figure 3. Schematics of support stand of propulsion system

A schematic of assembly of this stand is in Fig. 3. In order to reduce the sensitivity of pendulum and to remove the unwanted effects of external noises, a drowned fin in a water container was used.

Second sample. Stand for measuring thrust vector of laser and plasma micro-thrusters.

The short range of produced force in micro thrusters and high sensitivity on calculated thrust force comparing to external noises necessitates the need for different type of design for this kind of thrusters. According Hiroyuki et al. (2004) Researchers in Tokyo University have calculated the thrust force of two types of micro thrusters by designing a special stand.

This stand has a pendulum mechanism. The structure has one degree of freedom (rotating around the hinge). The investigated thruster is attached to one end of pendulum and on the other end, there is a balancing weight. As it's obvious in the picture two ends of the pendulum is bound by a damper and a transducer. The produced force is measured by the sensor and the data is transferred to main PC.

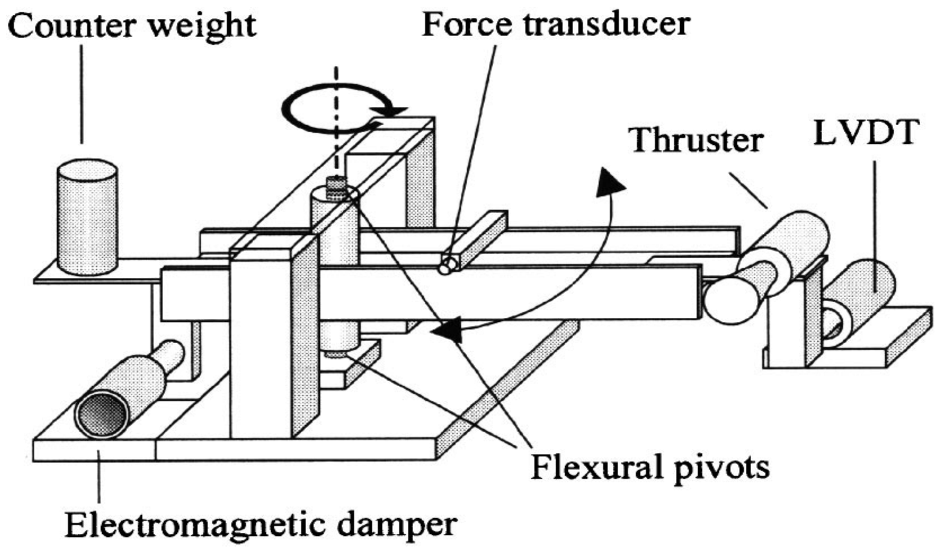


Figure 4. schematic view of Tokyo University stand (3)

Since other assemblies which were suggested in other academic references for measuring the thrust vector of space thrusters were similar, thus we decided not to mention these similar samples. According Diamant et al. (2010). (6), (7), (8), (9), (10), (11), (12).
Main problems in current systems can be summarized as bellow:
Reviewed stands, don’t have the ability of calculating the precise thrusting force in vector scheme (3D).
Reviewed stands, can only calculate the magnitude of produced force by thrusters in longitudinal axis. So none of them can calculate the eccentricity of force vector.
Considering that none of the reviewed samples can present a satisfying response to the problem (as mentioned in part 2) it is necessary to design a six-axis stand.

Introducing the six-axis stand for measuring thrust vector of cold gas thrusters

Lack of a six-axis stand for measuring the thrust vector of space thruster systems and inability of current stands in satisfying the needs of domestic space industries, persuaded us to design a six-axis space stand, as demonstrated bellow.
This stand has two main segments: mechanical and electronic:

Mechanical segment: This segment is a six-legged table which is inspired by Stewart platform. What is known as developed Stewart nowadays includes two rigid objects which are connected through six arms with spherical joints on both sides. Generally a Stewart consists of two rigid objects which are bound to each other by six geometrical constraints (Fig.5). One of these rigid objects is fixed and named the base and the other object is called moving platform and could be located according to six constraints.

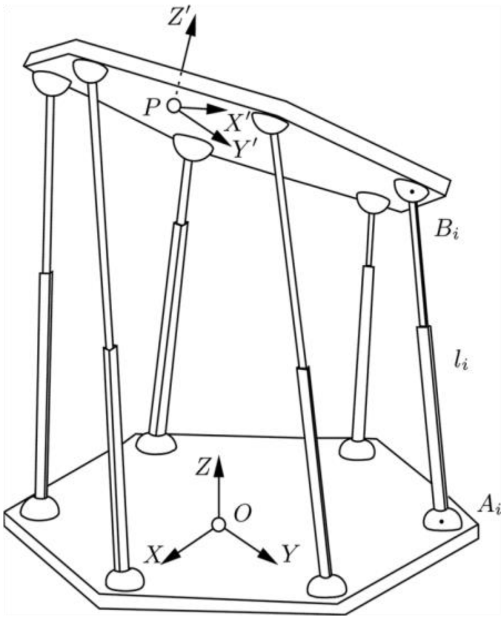


Figure. 5 schematic of a Stewart leg

Mentioned assembly, is the main segment of stand which the space thruster is installed on the top of upper plate. Since we need to assess six unknown components (3 components of locations and 3 components of force magnitudes) to calculate the thrust force of space thruster systems, it was necessary to use a platform which could be formulated with six equations. This six-legged table is used because after static modeling, six equilibrium equations will be at hand. The input of these equations is the axial force of table legs. So it would be necessary to design an approach to calculate the axial force of each leg precisely.

Electronic segment: This invention includes a central computer (equipped with a DAQ card) and six axial dynamometer sensors. Dynamometer sensors are installed alongside of each leg to calculate the exact magnitude of force in each axis. Measured data by these sensors will be transferred to central computer.
Test process is executed as bellow:
The center of space thruster nozzle is installed exactly on the center of gravity of upper plate of stand. Thruster is installed in a way that the reaction of produced force applies downward to the stand (i.e. the exhaust of nozzle faces up).
The thruster starts.
Performance of thruster will cause a change in axial force of each leg.
Implemented sensors sense the axial force of legs and transfer this data to the central computer.
Data of sensors will be processed by central computer.
According to the sensors’ gathered data and processes of central computer, the thrust vector of space thruster system will be calculated.

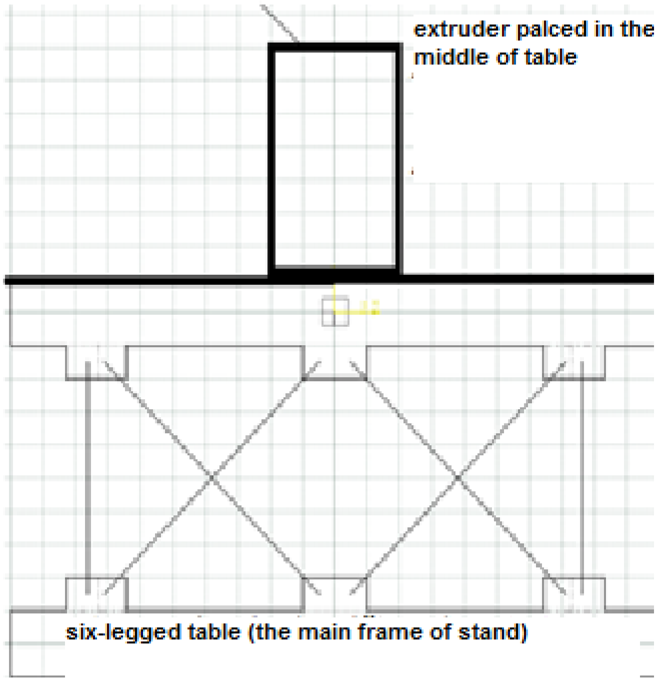


Figure 6. Front view of stand

Modeling of six-axis stand

To model the mentioned system and to obtain the equations it is necessary to complete 3 main steps. First, we should determine the input and output values and fixed parameters in equations. Then the equilibrium equations for each six legs of the table should be developed. At the final stage the set of equations should be solved with the data gathered by sensors and then unknown values will be determined.

First step

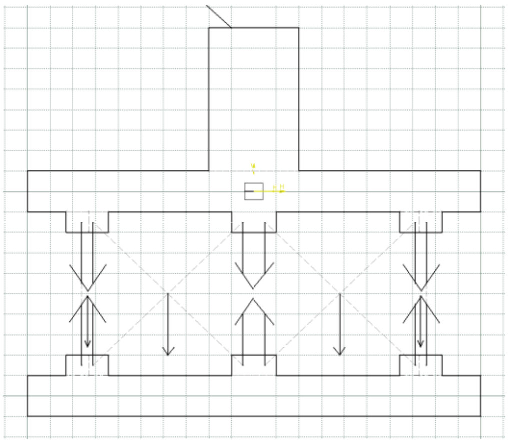
The inputs of this modeling are the sensed forces by sensors on legs (P_6, P5, P4, P3, P2, P1).

The outputs of this modeling are 3 location components of thrust vector point of exertion (z‹y‹x) and 3 magnitude components of thrust vector (T_z‹T_y‹T_x).

Effecting parameters in modeling are length, thickness and weight of each leg, weight of upper and lower plates, thickness of upper and lower plate, weight of cold gas system, weight and thickness of bearing.

Second step

In this step it would be necessary to calculate the equilibrium equations of stand (equations of each six legs and also for upper palate of Stewart). As a sample, the equation for one of legs is presented below:



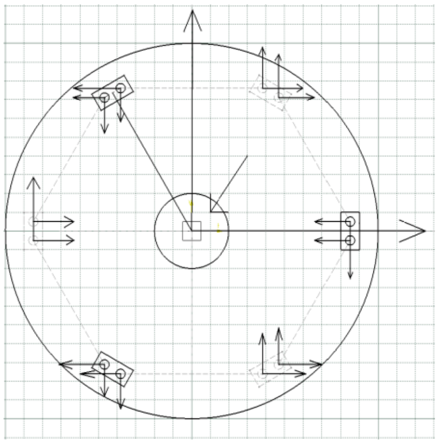


Figure 7. Top view of bar free forces diagram Fig. 8. Front view of bar free forces diagram

$$\sum F_x = -f_{x_1} + f'_{x_1} = 0 \quad (1)$$

$$\sum F_y = -f_{y_1} + f'_{y_1} = 0 \tag{2}$$

$$\sum F_z = -f_{z_1} + f'_{z_1} - W_{beam} = 0 \tag{3}$$

$$\sum M_1 = f_{x_1}\cos(60)\sin\left(\frac{\pi}{2} - \theta\right) l_{beam} - f_{y_1}\cos(30)\sin\left(\frac{\pi}{2} - \theta\right) l_{beam} - f_{z_1}\sin(\theta) l_{beam} - W_{beam}\sin(\theta)\frac{l_{beam}}{2} = 0 \tag{4}$$

$$\sum M_2 = \left[f_{x_1}\cos(30) + f_{y_1}\cos(60)\right] l_{beam} = 0 \tag{5}$$

Third step

According to previous steps and developed equations, an algorithm for calculating thrust force vector is derived. This algorithm, by using input data from sensors solves the equations set of stands and determines the thrust vector.

Conclusion

State needs in precise calibration (vector calibration) of thrusters, had been the main concern in designing a six-axis stand for the authors. Because the statistical surveys about current stands haven't present desirable results, a creative design for calculating thruster force vectors was suggested. This stand, utilizing a similar platform like six-legged table (Stewart) and by placing dynamometer sensors on each leg, calculates the exact vector of thrust force. By developing a static modeling for the mentioned table and by providing algorithmic software, now we have access to a lab for calibration of space thrusters.

References

A.Nobinzadeh and Abedi, S. (2012). modeling and design of the thrust vector measurement of cold gas thruster; Thesis, School of Aerospace K.N.Toosi University of Technology.

Dalvand Rahimi, M. (2014), analysis of multi-axial thrust vector measurement for cold gas thrusters. Thesis. Chief, Department of Aerospace K.N.Toosi University of Technology.

Delvand Rahimi, M.(2013), analysis and design of a hardware-in-the-loop system for spacecraft ADCS system. Thesis, Aerospace department of Amirkabir University of Technology.

Diamant, Kevin D., et al (2010). "Thrust Stand Characterization of the NASA Evolutionary Xenon Thruster (NEXT).

Zandbergen, B. T. C., et al. "Test facility development for testing of micro-thrusters at TU-Delft." 6th Inter-national Spacecraft Propulsion Conference. San Sebastian, Spain, 2010.

Willis III, William D., Charles M. Zakrzwski, and Stephen M. Merkowitz (2002). Development of a thrust stand to meet LISA mission requirements." 38th AIAA Joint Propulsion Conference.

Larangot, B., et al (2002). Solid Propellant MicroThruster: an alternative propulsion device for nanosatellite. Aerospace Energetic Equipment Conference (Avignon, France).

Haag, Thomas W (1997). Thrust stand for pulsed plasma thrusters.Review of Scientific Instruments 68.5 (1997): 2060-2067.

Nothnagel, Sarah Lynn (2011). Development of a cold gas propulsion system for the talaris hopper. Diss. Massachusetts Institute of Technology.

S.Ciaralli, M.Coletti, and S.B.Gabriel (2013). µ-PPTs diagnostics: a high accuracy impulsive thrust balance. 33rd International Electric Propulsion Conference, Washington D.C., USA, October 6- 10, 2013, IEPC-2013-165.

Koizum Hiroyuki, Kimiya Komurasaki, and Yoshihiro Arakawa (2004). Developments of thrust stand for low impulse measurement from microthrusters. Review of scientific instruments 75.10: 3185-3190.

Lugini, Claudio, and Marcello Romano (2009). A ballistic-pendulum test stand to characterize small cold-gas thruster nozzles.. ActaAstronautica 64.5: 615-625.