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A BIBLIOMETRICS ON HALL THRUSTER CONTROL SYSTEMS

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Abstract: Hall thrusters need control systems for some of their subsystems to ensure their complete operation. However, at least in the last fifteen years, few papers can be found on this topic. This work presents a review of applications of control systems in Hall thruster subsystems. In this scenary, articles from the period 2008 to 2022 were searched in a database, and the applications were identified and analyzed. In this case, a synthesis was done to bring together the different applications and considering the main bibliometric data that can be extracted. Therefore, this work presents trends in the area and offers a synthesis that has high potential to be useful for future research.
Keywords: Control Systems, Hall trunster, Aerospace, Review

INTRODUCTION

With the aim of achieving high exhaust speeds, electric propulsion technology results in a considerable reduction in the mass of propellant required for space applications, compared to conventional methods. The lower mass can reduce launch costs in order to deliver the desired object to some orbit or to some point in deep space [1].

Electric thrusters produce charged particles and accelerate them, providing thrust. In this case, a propellant gas is ionized and gives rise to plasma by forming ions and electrons. The charged particles of the plasma move due to electric and magnetic fields generated by themselves or externally. The plasma is nearly electrically neutral, i.e., the densities of ions and electrons are approximately equal (quasi-neutrality) [1]. To be called a plasma, an ionized gas must satisfy three conditions [2]:

a) System dimensions must be much larger than the charged particle region.

b) The number of charged particles must be very large.

c) Collisions of charged particles with neutral par ticles must be few.

Examples of electric thrusters [1] are Resistojet and Arcjet (electrothermal type); Ion Thruster, Hall Thruster and Field Emission Thruster (electrostatic type); PPT and Magnetoplasmadynamic Thruster (electromagnetic type).

Hall and ion thrusters are the best performing electric thrusters in terms of thrust, specific impulse and efficiency, and most widely used in space applications. The specific impulse consists of dividing the propellant exhaust velocity by the acceleration due to gravity. Although the Hall thruster has a slightly lower efficiency and specific impulse than the ion thruster, its advantages are due to the fact that, for certain power values, its thrust is greater and the device has a simpler design and, In its operation, it requires fewer power supplies [1].

As mentioned, Hall thrusters (Figure 1) are a type of electric thruster [1, 3–7], and their use is more common in the correction of attitude and orbit in artificial satellites and propulsion of space probes [4, 5, 8–10]. The first Hall thrusters were tested in flight in the 1960s [1, 3, 4, 11]. The physical form of a Hall thruster generally consists of (a) a cylindrical channel, (b) an anode at the bottom of the channel, (c) a magnetic field inside the channel, and (d) an external cathode [1]. The operation consists of injecting a neutral gas into the channel, emitting electrons from the cathode towards the anode; in this way, the thruster confines the electrons in a Hall **ExB** current that creates a virtual cathode above the anode. Then, the electric field between the anode and the virtual cathode accelerates the ions out of the channel, thus generating thrust.

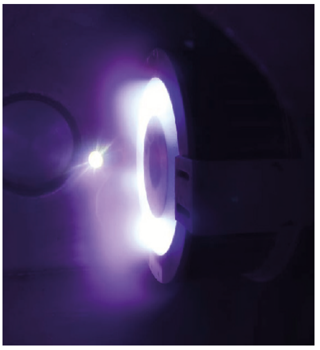

Fig. 1 Side view of PHALL II-C in operation (Plasma Physics Laboratory, University of Brasilia, Brazil)

Plasma Physics Laboratory at the Physics Institute of the University of Brasilia (PPL/PI/UnB) has been developing Hall thrusters since 2004 [4, 5, 8, 12]. This project, called PHALL, is incremental. PHALL I, PHALL II-A, PHALL II-B and, the most recent version, PHALL II-C (Figures 1 and 2) have already been developed. The most recent version is classified as TRL 3 (Technology Readiness Level, NASA) and the next version, PHALL III [4], developed with the support of the Brazilian Space Agency (AEB), is planned to reach TRL 6. This version will be more compact and efficient. The ultimate goal is to have qualified for space flights with TRL 9 classification, a Hall thruster for micro and small artificial satellites. Other PPL works include an HPT thruster (Figure 3) in different versions, elimination of biological contaminants using plasmas and the deposition of thin carbon films.

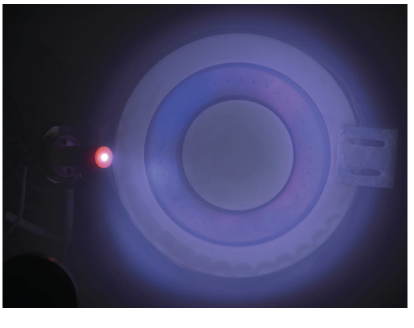

Fig. 2 Front view of PHALL II-C in operation (Plasma Physics Laboratory, University of Brasilia, Brazil)

Hall thrusters are devices that have several subsystems requaring controllers for full operation. The article presents a review of the control systems for Hall thruster subsystems, in the 15 years from 2008 to 2022, with the objective of presenting research trends in the area and a synthesis for the consultation of future works. Control systems that control (a) the hollow cathode, (b) the ionization oscillations, (c) the low frequency discharge current oscillations, (d) the magnetic field, (e) the mass flow, (f) the discharge voltage and (g) the solar panel peak point were found and researched.

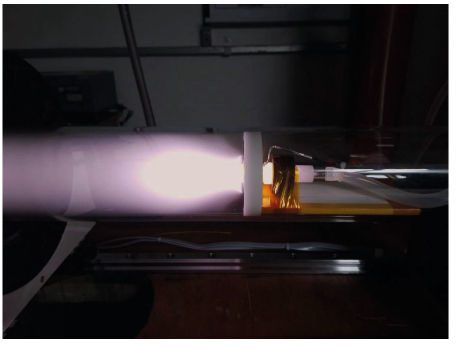

Fig. 3 HPT thurster in operation (Plasma Physics Laboratory, University of Brasilia, Brazil)

The remainder of this paper is divided as follows: Section 2 presents the methods used in this research, Section 3 describes the results obtained from the bibliometric research on the topic of Hall Thurster Control Systems, Section 4 discusses the results obtained, and finally, Section 5 shows our conclusions.

METHODOLOGY

For this work, the following method was used:

a) Articles were searched on the Web of Sci ence website, accessing it from the Capes (Coordination for the Improvement of Higher Education Personnel) database website, Brazil: http://www.periodicos.capes.gov.br/. The Web of Science is one

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of the largest databases of articles, so this database was chosen for the research;

b) as input, the expression "Hall Thruster Con trol" was used, aiming to select articles that dealt with the development of control systems for subsystems of Hall thrusters;

c) articles from 2008 to 2022 (15-year interval) were selected. The last fifteen years were chosen with the intention of avoiding including types of research that are no longer trending in the area of control in Hall thrusters;

d) a total of 74 articles were considered that, initially, had chances to cover the research topic;e) these articles were studied and those that actu ally dealt with the proposed topic were filtered.

REVIEW

This section presents the developed control system works available in the researched literature, as well as their purpose, main characteristics, main conclusions of the respective work, and information such as the journal of origin and its impact factor. The control systems are ordered in descending order of the impact factor of the journal in which the article was published.

SYNTHESIS OF THE CONTROL SYSTEMS

CONTROL SYSTEM OF THE HOLLOW CATHODE

This control system, presented in the article [13], aims to heat and ignite the hollow cathode and keep it on. The main characteristics of this control system are:

a) an improvement proposed in this research was the union of the three energy sources (one for the heater, one for the combustion, and one for the maintainer) in a single source through control with three loops;

b) such control has a PID controller in each loop; c) there are two loops used for current control and one loop for voltage control.

The main conclusions reached in the work are: in comparison with conventional control systems (separate sources) there was an improvement in power density, efficiency, and dynamic response; with maximum efficiency of 89.7%, increasing by 3.9% to 14.2%. The journal of origin is the *IEEE Transactions on Power Electronics* and its latest impact factor, in 2021, is 5.967 (see Fu et al. bar in Figure 4).

CONTROL SYSTEM OF THE MAGNETIC FIELD

The control system presented in [14] has the purpose of performing the suppression of the breathing mode oscillation. Its main features are:

a) the discharge circuit is placed in series with the electromagnetic coils;

b) the dominant physical mechanism to explain the suppression of the breathing mode oscillation is the closed-loop feedback of the magnetic field on the ionization process.

The control system was analyzed through experiments and simulations and it was concluded that the control system reduces the amplitude of oscillation of low-frequency breathing mode, having as cause the condensation of the movement of the ionization front. The journal where the work is presented is the *Journal of Vacuum Science and Technology* and its impact factor is 3.234, in 2021, (see Liqu. et al. bar Figure 4).

CONTROL SYSTEM OF THE DISCHARGE VOLTAGE AND CONTROL SYSTEM OF THE SOLAR PANEL PEAK POINT

In the work of [15], two control systems were developed: (a) the discharge voltage and (b) the peak point of the solar panel. This work was published in the journal *Acta Astronautica* with an impact factor (in 2021) of 2.954 (see Reza et al. bar in Figure 4). Next, we describe the two aforementioned approaches.

a) Control system of the discharge voltage

This control system is intended to maintain the discharge voltage at a fixed value. Its main characteristic is the modification of the mass flow rate of the propellant gas that crosses the anode until the target voltage is reached.

In this case, a characterization experiment was carried out with the following conclusions: the voltage control was successful in changing the operating point by acting on the mass flow rate of the propellant gas in the anode, remaining in operation at several points for long periods of time, for example, 750 s at 280 V and 2500 s at 300 V. Additionally, no major problems were found regarding thruster stability or system regulation.

b) Control system of the solar panel peak point

The purpose of this control system is to keep the solar array simulator at the maximum power point. Its main characteristic is that the system performs a variation in the propellant mass flow rate by evaluating the derivative of the power in relation to the discharge voltage; such derivative must remain at zero value; if it increases, the propellant mass flow rate decreases and, if the derivative decreases, the rate increases.

In this case, the conclusion is that this type of control makes it possible to control the thruster even in the most severe condition of a sudden change in the performance of the solar arrays; which can provide, mainly at the beginning of the life of the spacecraft, benefits to it in terms of regarding the full use of the capabilities of such solar arrays.

CONTROL SYSTEM OF THE LOW-FREQUENCY DISCHARGE CURRENT OSCILLATION

The control system developed in [16] aims to dampen low-frequency discharge current oscillations. As main characteristics, two PID controllers were simulated, one on the voltage output and the other on the magnetic field output.

The main conclusions of the work are that the PID controllers (in voltage and magnetic field) proved to be much more effective than RLC networks. The PID control over the magnetic field was slightly better than the PID control over the voltage output; despite this, the latter becomes a better option since the magnetic field has complex physics.

Journal of Applied Physics, the source journal of the work, has an impact factor of 2.877, in 2021, (see Bar. and MIE. bar in Figure 4).

CONTROL SYSTEM OF THE IONIZATION OSCILLATION

According to [17], where the control system is presented, the purpose is to dampen discharge current oscillations. In this case, its main characteristic is a PID controller that acts on the discharge voltage.

The work has as the main conclusion that the control system with PID controller, in comparison with the normal operation, did not show evidence of improvement or worsening in the performance. However, damping is most effective with pure proportional control in theoretical considerations and numerical simulations.

The journal Physics of Plasmas, where the article was published, has an impact factor of 2021 of 2.357 (see Bar. and Kacz. bar in Figure 4).

CONTROL SYSTEM OF THE MASS FLOW

In the work described in [18], the purpose of the control system is to prevent thermal runaway in a direct evaporation supply system and to stabilize the discharge current during voltage-limited operation.

The main characteristics are that to enable the automatic operation of the mass flow control system, a PID controller was implemented through an algorithm; the measured variable was the discharge current and the controlled parameter was the anode heater current. The most relevant conclusion is that the control system had a low consumption of the total power of the system during steady-state operation.

The source journal is the Journal of Propulsion and Power with a current impact factor, in 2021, in the amount of 2.005 (see Hopkins et al. bar in Figure 4).

SYNTHESIS

As a synthesis of the bibliometrics research, summary tables (Tables 1 to 7) of the researched control systems are presented with their purposes, main characteristics, and main conclusions of the works.

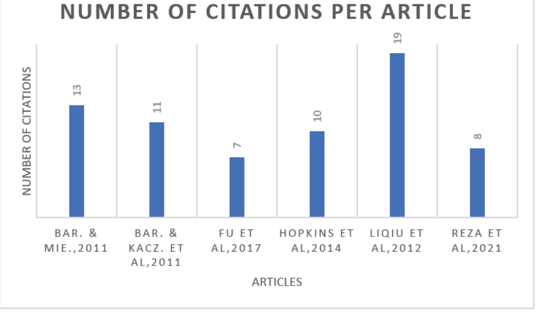

Fig. 5 Number of citations per article.

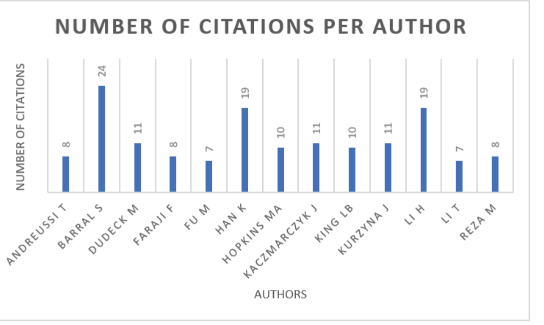

Fig. 6 Number of citations per author.

BIBLIOMETRIC DATA

The Figures 4 to 11 present bibliometric data on impact factor per article, number of citations per article, number of citations per author, number of articles per author, number of publications per year, number of articles per country, number of articles per field and number of articles per institution (respectively).

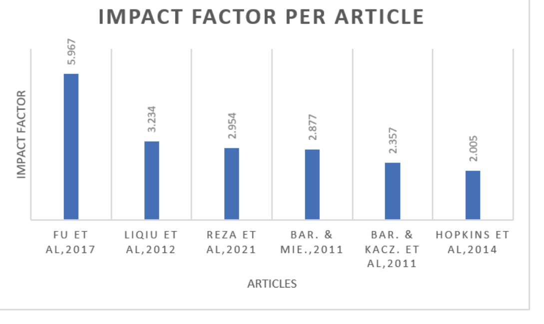

Fig. 4 Impact factor per article

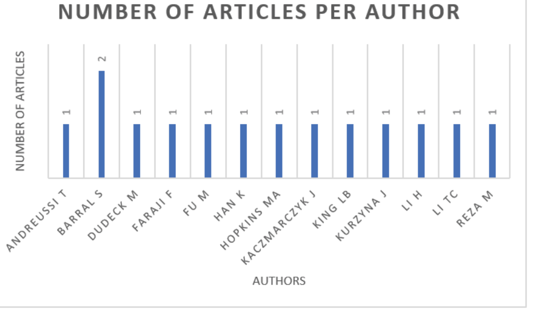

Fig. 7 Number of articles per author.

DISCUSSION

From 74 articles consulted, only 6 fulfilled the research requirements; that is, identification of the works developed in control systems for Hall thrusters subsystems in a 15-year interval. It can be observed that the amount was low, both in absolute terms and in relative terms (8.1% of the cases researched). This fact already shows that there is little research in this area and, therefore, there is a gap to be filled in it. It was not possible to know, from the articles consulted, why there was so little research in the area.

Goal	Main Characteristics	Main Conclusions
Carry out heating and ignition of the hollow cathode and keep it on.	Union of the three energy sources in a single source and use of PID controllers with three loops.	Improved power density, efficiency and dynamic response.

Table 1 Hollow Cathode Control System [13], Impact Factor of the journal: 5.967.

Goal	Main Characteristics	Main Conclusions
Perform Suppression of breathing mode oscillation.	The discharge circuit is placed in series with the electromagnetic coils.	Reduces oscillation amplitude.

Table 2 Magnetic Field Control System [14], Impact Factor of the journal: 3.234.

Goal	Main Characteristics	Main Conclusions
Keep the discharge voltage at a fixed value.	Modifying the rate of mass flow of the propellant gas through the anode until the target voltage is reached.	Successful change of operating point, and no major problems were encountered regarding thruster stability or system regulation.

Table 3 Discharge Voltage Control System [15], Impact Factor of the journal: 2.954.

Goal	Main Characteristics	Main Conclusions
Keep the solar array simulator at the maximum power point.	The system performs a variation in the propellant mass flow rate by evaluating the derivative of the power in relation to the discharge voltage.	This type of control makes it possible to control the thruster even in the most severe condition of a sudden change in the performance of the solar arrays.

Table 4 Solar Panel Peak Point Control System, [15], Impact Factor of the journal: 2.954.

Goal	Main Characteristics	Main Conclusions
Keep the solar array simulator at the maximum power point.	The system performs a variation in the propellant mass flow rate by evaluating the derivative of the power in relation to the discharge voltage.	This type of control makes it possible to control the thruster even in the most severe condition of a sudden change in the performance of the solar arrays.

Table 5 Low Frequency Discharge Current Oscillation Control System [16], Impact Fator of the journal: 2.877.

Control systems are important for the complete operation of a Hall thruster. Additionally, they can improve the performance in several aspects. In the case of Hall thrusters, for example, it can increase their lifetime. Therefore, due to the existing gap, important research can be done in this area to do considerable improvements in Hall thrusters.

Goal	Main Characteristics	Main Conclusions
Damp discharge current oscillations.	PID controller that acts on the discharge voltage.	Pure proportional control is more effective.

Table 6 Ionization Oscillation Control System [17], Impact Factor of the journal: 2.357.

Goal	Main Characteristics	Main Conclusions
Prevent thermal escape in a direct evaporating feed system and stabilize discharge current.	An algorithm was used to implement a PID controller.	Low total system power consumption during steady-state operation.

Table 7 Mass Flow Control System [18], Impact Factor of the journal: 2.005.

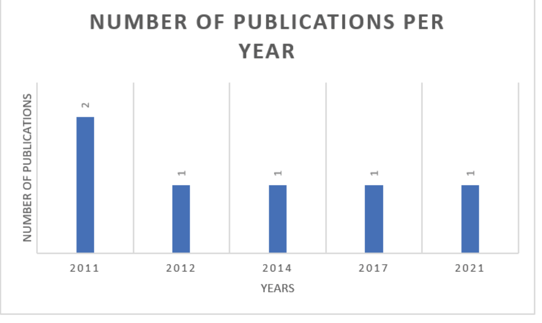

Fig. 8 Number of publications per year.

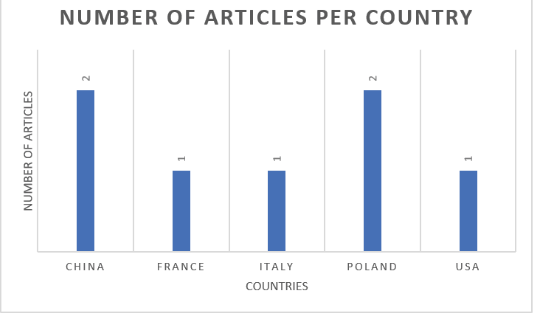

Fig. 9 Number of articles per country.

For instance, Figure 5 shows that the highest number of citations occurs in articles by [14], with 19 citations; [16], with 13 citations and [17], with 11 citations. The three articles deal with the same topic: "damping of current oscillations". This fact shows that this topic is the biggest research trend in the area. This tendency is also mentioned in

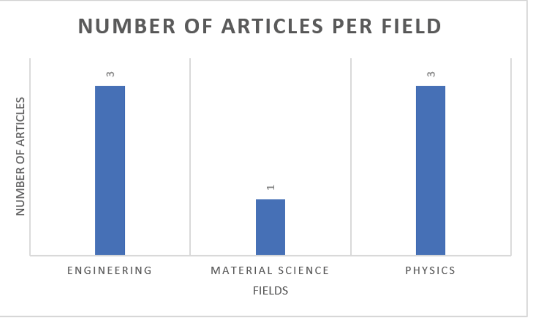

Fig. 10 Number of articles per field.

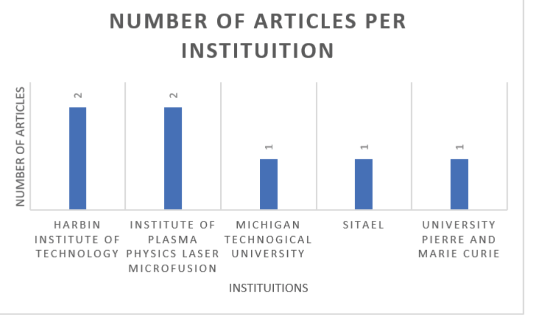

Fig. 11 Number of articles per instituition.

[14]. Additionally, according to the same article, such research is important given that these oscillations can affect the power processing unit, making a reduction in the specific thrust, efficiency and lifetime of the Hall thruster, in addition to controlling electromagnetic compatibility with other equipment installed on satellites. Another fact that reinforces this trend is the finding that 4 of the 6 papers presented (66.7%) had this topic as their purpose.

It was also found that in 3 of the 6 works (50.0%) PID controllers were tested. It is a type of popular and conventional controller with a suboptimal response. Thus showing that much can still be done in terms of using varieties of controllers, such as more robust controllers, aiming for optimized responses.

It is also verified that the review presented a different journal for each work and showed the IEEE Transactions on Power Electronics as the main journal ([13]) in the area, given that it has the highest impact factor (Figure 4).

It can be seen that Barral is the author with the highest number of publications (Figure 7) and that his articles are the most cited (Figure 6), with 24 citations. Therefore, Barral appears as the main author of the area.

It is also found that, according to Figure 8, although the research was carried out for the period from 2008 to 2022, production is concentrated in the period from 2011 to 2021, with greater production in the period from 2011 to 2012, with 3 of 6 works (50.0%). The main countries in the development of works (Figure 9) were China and Poland with two articles each. It is also verified (Figure 11) that the main institutions are the Harbin Institute of Technology and the Institute of Plasma Physics Laser Microfusion with 2 works each. Finally, it appears that, despite control systems is an engineering problem, this topic has been well accepted in journals in the field of physics (Figure 10).

CONCLUSION

The present work proposed to carry out a review of control systems for Hall thruster subsystems in the 15-year interval from 2008 to 2022. In this case, 74 articles were consulted and only 6 articles were found in the area. The control systems found and analyzed were: the hollow cathode, the ionization oscillations, the low-frequency discharge current oscillations, the magnetic field, the mass flow, the discharge voltage, and the solar panel peak point.

In addition, 4 papers talk about very similar subsystems, showing a tendency to work on controlling current oscillations. It was also found that the PID controller was the most used (3 works).

Barral was also found to be the main author.

As a way of directing new research in the area of Hall thruster control systems, it is added that the very low amount of work already developed shows the existence of a large gap in the area, where important research can be carried out to achieve considerable improvements in Hall thruster performance using control systems. Furthermore, basic controllers were generally used in the researched works. It also shows that a lot of research is carried out with varieties of controllers, such as, for example, more robust controllers with optimized responses.

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