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Engineering Notes

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Discharge Frequency Modulation of Pulsed Plasma Thruster

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Introduction

PULSED plasma thrusters (PPT) are pulsed electric propulsion devices that can provide high specific impulse at low power levels. In a PPT, the power throttling is managed simply by adjusting the pulse repetition frequency and does not affect the performance. Therefore, PPTs can generate small impulse bits and precise, arbitrary impulses. Because of these properties of PPTs, the satellite and other interplanetary classes of mission present excellent opportunities for their application.[1–10] In recent years, PPTs have attracted great attention as promising thrusters.[1–6,8] The rapid growth in the small satellite community and the broad range of applications entails an improvement in terms of reduced dry mass, increased lifetime, and increased performance in PPT technology.[1,2]

To date, most PPTs are ablative devices that accelerate solid propellant through electromagnetic forces. A PPT consists of a pair of electrodes between which a bar of solid propellant, typically Teflon®, is fed. The electrodes are connected to a charged capacitor. Normally, spark plugs are used to provide a large supply of free electrons to initiate an electric discharge between the electrodes,[8–11] across the exposed surface of the Teflon. The very high temperature of the discharge plasma causes evaporation of the propellant, which is then accelerated by the electromagnetic and pressure forces[8] and, thus, produces thrust. The main advantage of this class of thrusters is their simplicity because they use solid Teflon as propellant. Therefore, as compared to conventional propulsion systems, the PPT eliminates the need for distributed and/or toxic propellant systems.[8] In addition, their pulsed nature and lower power levels permit operation over a relatively broad power range without much loss of performance.[8]

Being an electric propulsion system, the electrical circuit parameters, for example, capacitance, inductance, resistance, power, etc., play an important role in the performance of a PPT. Solbes and Vondra[12] have studied the effect of electrical circuit parameters on the performance of a PPT, for example, impulse bit, specific impulse, and efficiency. Pulumbo and Guman[13] have conducted studies on the effect of propellant and electrode geometry on PPTs. These studies have helped in improving the performance and understanding of PPTs. Aston and Pless[14] have concluded that the life of a PPT is limited by the ignition circuit. They have conducted tests to study the igniter plug deposition, erosion, and the manner in which the igniter plug is initiated.[14] The results of these tests indicate that inductive rather than resistive coupling of the igniter plug to the thruster cathode, and the use of a high-current, short-pulse-length trigger circuit, offer significant increases in igniter plug lifetime. However, their study was focused on increasing the lifetime of the spark plug, and no experiments were conducted to analyze the dependence of the discharge frequency of the PPT on the pulse duration of the spark plug. Burton and Turchi[8] have speculated that the exact conditions of igniter plasma should not directly affect the performance of the PPT because the energy and mass associated with this spark are much smaller than the corresponding values for the main discharge. However, they have stated that the actual mechanism by which the igniter starts the PPT discharge is not very well understood to date. The present study aims at understanding this dependence of the PPT discharge frequency on the pulse frequency of the spark plug, which can help in better understanding the role of the igniter plug in the discharge initiation of the PPT.

Although spark plugs are known to be the life-limiting components of the PPT,[14] they are extensively used because of unavailability of any other suitable alternative. Studies have been conducted to investigate other options available for discharge initiation.[15,16] It has been demonstrated that a discharge can be initiated in a PPT at an undervoltage by shining an infrared laser pulse on the thruster's backplate.[15] However, this idea is in the nascent stage and is currently not viable for space applications. Studies have also demonstrated the feasibility of a self-triggering design where the voltages in the electrodes can exceed the breakdown voltage of the discharge gap. The need for the voltage exceeding the breakdown voltage of the gap entails a requirement for a high-voltage power supply.[16] However, in a self-triggering design, the ignition circuit is not needed. In the absence of discharge-initiating circuit, controlling the frequency of pulse discharge becomes a problem. The frequency of discharge is important from the thrust-generation point of view.[17] A method was suggested for pulse modulation by Dubey et al.[16] by varying the initial supply voltage and capacitance. However, varying the initial supply voltage and capacitance involves complexities such as the use of a capacitor bank and a high-voltage power supply. This paper suggests the modulation of PPT discharge pulse, within a limit, without the need for a capacitor bank. This might result in a reduction in the mass of the system and will also reduce the unnecessary complexities associated with it. In addition, the use of a spark plug will result in PPT discharge at relatively lower voltages, which implies that one would not need a very high-voltage power supply.

Igniter plugs initiate PPT discharges by providing a large supply of free electrons to start an avalanche. The study presented in this paper involves creating a pulse of electrons that would alter the space charge characteristics of the discharge gap, thus lowering the breakdown voltage. If the discharge gap is initially placed at an undervoltage, a voltage slightly less than that required for discharge without the electron pulse and greater than the breakdown voltage necessary with the electron pulse, the electron pulse will successfully initiate the discharge. Therefore, the igniter plug pulsation can be used to modulate the frequency of discharge in the PPT because the pulsation gives a periodic supply of large number of electrons needed for discharge initiation.

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In the present effort, experiments were conducted to study the effect of varying pulse frequency of the igniter plug on the discharge frequency of the PPT. Both the frequency and the input voltage to the igniter plug were varied. Results show that the discharge frequency of the PPT depends on the pulse frequency of the spark plug. However, the discharge frequency of the PPT did not depend on the input voltage (power) to the spark plug. Thus, by controlling the pulse frequency of the spark plug, one can vary the discharge frequency of the PPT over a range.

Experimental Details

For the experiments described hereafter, a fixed geometry parallel rail thruster was designed. A Teflon bar was used as the propellant. Two copper electrodes (36 mm apart, 12 mm wide, and 50 mm long, as shown in Fig. 1) were connected to a 2.5-kV, 40-μF capacitor that discharged across the Teflon. The PPT discharge was initiated by using a commercially available automotive spark plug connected to a specially developed electrical circuit. The input voltage and spark plug pulsating frequency were varied using a square waveform of given peak-to-peak voltage and frequency using a function generator. The experiments were conducted in a cubical chamber of 29-cm sides. The chamber was evacuated to a pressure of 50 Pa by using a vacuum pump.

A high-voltage output dc–dc converter was used as the main voltage supply that converts an input voltage between 4 and 30 V to a very high-voltage output on the order of a few kilovolts dc. A schematic of the power supply circuit is shown in Fig. 2. The output voltages from the power supply were measured to be equal to 1.3 and 3 kV for input voltages of 4 and 12 V, respectively. The current consumption was quite low at 1.5 A. The device essentially works by chopping the input dc voltage at the designed frequency and applying this to the transformer to step it up to some intermediary high voltage. Then, there is a voltage multiplier portion of the circuit that further multiplies as well as rectifies the transformer output to give the desired very high dc voltage output. The circuit is wired on a specially designed printed circuit board. The whole device is quite rugged and has been tested extensively.

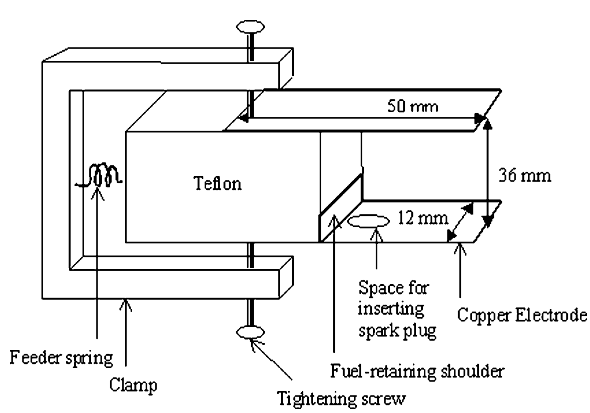


Fig. 1 PPT configuration.

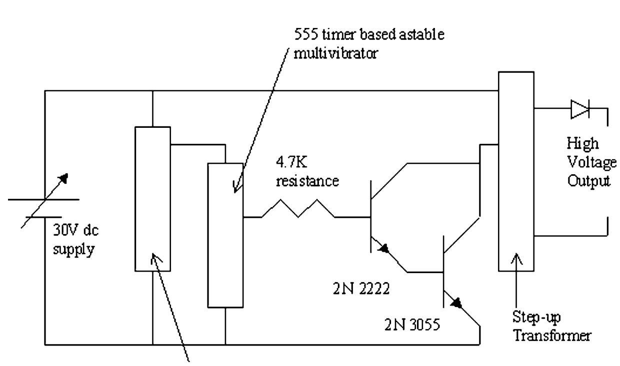


Fig. 2 Schematic of circuit of high-voltage power supply.

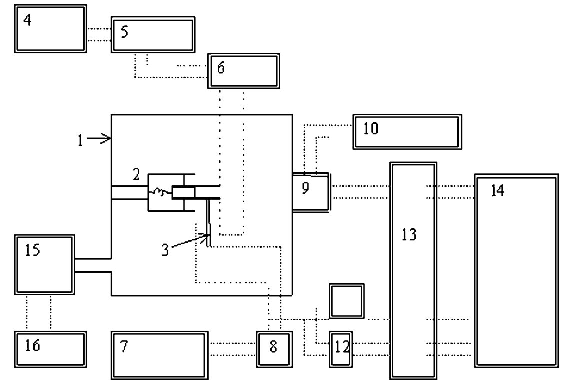


Fig. 3 Block diagram of experimental setup used in study: 1, vacuum chamber; 2, PPT; 3, spark plug; 4, 30-V dc power supply; 5, dc–dc converter; 6, capacitor; 7, 20-V dc power supply; 8, spark plug circuit; 9, photodiode; 10, 12-V dc power supply; 11, rheostat; 12, potentiometer; 13, buffer; 14, personal computer with DAQ card; 15, vacuum pump; and 16, 220-V, 50-Hz ac.

In the present study, the effect of the igniter plug frequency and the power input to the igniter plug was seen on the discharge voltage of the PPT and also on the frequency of the PPT. The complete schematic of the experimental setup is shown in the Fig. 3. A photodiode was used to measure the intensity of light emitted by the discharge of the PPT. A data acquisition (DAQ) card acquired the voltage signals from the photodiode, and the data were stored in a computer. The fast Fourier transform (FFT) analysis of the collected data was used to estimate the discharge frequency of the PPT.

The data acquisition program was manually stopped after 10 successive discharges were made by the PPT for a given combination of the pulse frequency of the spark plug and its input voltage. The data acquisition rate was kept constant; therefore, the number of data points acquired during 10 discharges gave a fairly good indication of the variation of the discharge frequency with the variation in the spark plug parameters.

For the analysis of the data, it was assumed that the data acquisition rate is n scans per second. This implied that if x number of data points were stored for 10 discharges, then the frequency of discharge would be $10 \times n/x$. Because the factor n was constant for the experiments, the frequency was factored by n to get nondimensional frequency. In the array of data points, the index number of a given data point gives an indication of the time at which the given data were acquired. This index number is equivalent to time, and so the index number of the data point has been termed nondimensional time. This was used to countercheck the results obtained from the FFT analysis.

In the present set of experiments, in contrast to the conventional procedure of storing the energy in a capacitor and then starting the spark plug, the igniter plug and the capacitor were simultaneously activated. This arrangement helped in continuously monitoring the input voltage and input current to the spark plug. In addition, the capacitor would charge and discharge continuously; thus, it helped in estimating the frequency of discharge for different pulse frequency and input voltage to the spark plug. Through this arrangement, a single capacitor can be continuously charged and discharged with a spark plug functioning in parallel. It also gave an indication of the minimum cutoff energy that must be provided by the capacitor for the spark plug to initiate a discharge.

The data were collected for the various combinations of input voltage to the spark plug circuit and the frequency of the spark plug. The input voltage was varied from 6 to 10 V in 2-V steps. For each voltage level, data were collected for 1, 5, 10, 25, and 50 Hz. The various samples of data thus obtained were qualitatively analyzed to study the effect of the aforementioned parameters. The voltage and current data were used to calculate the power input to the spark plug.

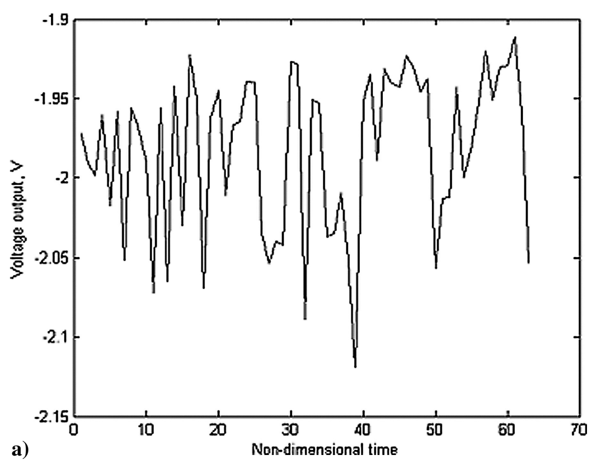
Note that because the parameter of interest in this study was the pulsating frequency of the PPT and not the actual voltage signal level from the photodiode, the results were highly repeatable with nonexisting statistical scatter.

Results and Discussion

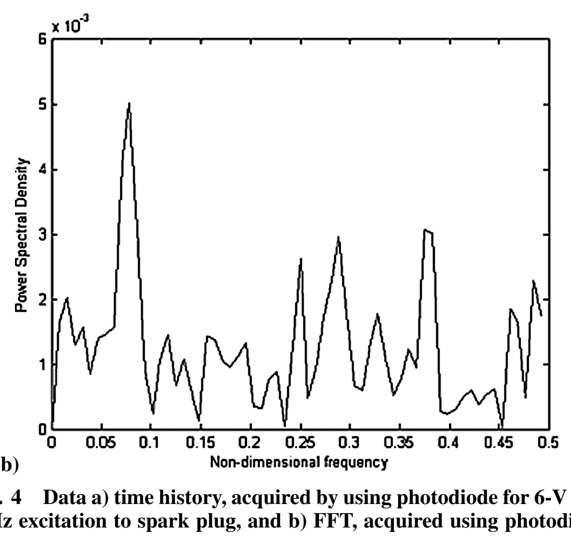
Effect of Igniter Plug Frequency on PPT Discharge Frequency

To observe the effect of the pulse frequency of the spark plug on the discharge frequency of the PPT, the voltage data obtained from the photo diode response were analyzed. An example of the data thus collected is shown in Fig. 4a, which corresponds to an input voltage of 6 V and a frequency of 1 Hz. The FFT analysis of the data was performed to obtain the nondimensional frequency of the discharge of the PPT, as shown in Fig. 4b. The frequency at which the highest peak was obtained was considered to be the nondimensional frequency of the discharge.

All of the experimental data are compiled in Fig. 5, which shows that the frequency of discharge of the PPT varies with the pulsation frequency of the spark plug. The actual PPT pulsating frequency was obtained by multiplying the nondimensional frequency by the scan rate factor, which was equal to 10 in this study and was estimated manually using a stopwatch. It was observed that there exists a value of the spark plug frequency for which the discharge frequency of the PPT was at a minimum. This frequency was termed the critical frequency of the spark plug. At the frequencies lower than the critical frequency, the discharge frequency of the PPT increased with the decrease in the spark plug pulsating frequency. These frequencies were termed subcritical frequencies. For the frequencies higher than the critical frequency, the discharge frequency gradually increased with the increase in the spark plug pulse frequency and finally tended to attain a limiting value at higher frequencies. These frequencies were termed supercritical frequencies.



a)



b)

Fig. 4 Data a) time history, acquired by using photodiode for 6-V and 1-Hz excitation to spark plug, and b) FFT, acquired using photodiode for 6-V and 1-Hz excitation to spark plug.

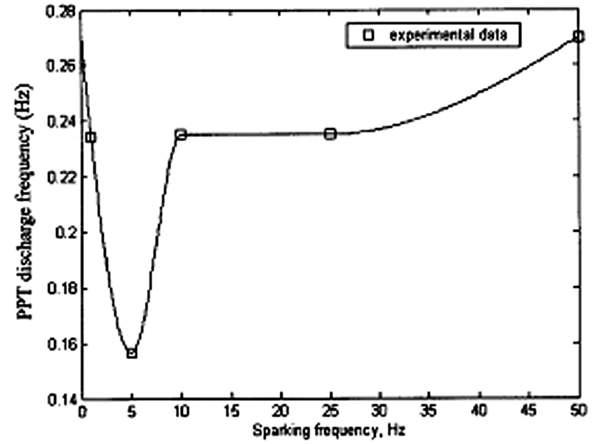


Fig. 5 Effect of spark plug's pulsation frequency on discharge frequency of PPT for spark plug excitation voltage of 8 V.

The discharge in the gap between the electrodes occurs whenever there is a dielectric breakdown in the gap. The dielectric breakdown occurs by either maintaining a very high potential difference between the two electrodes of the PPT, or the breakdown can be initiated at a relatively lower potential difference by ejecting a large number of free electrons in the gap using a spark plug. The threshold energy level is the minimum energy that a capacitor must supply for a discharge to occur, with a spark plug pulsating at a given power output level. The spark plug output voltage level and its pulse frequency determines the number and the energy level of the free electrons thus ejected. Thus, the discharge in the gap between the electrodes of the PPT occurs when the following conditions are simultaneously met:

1) The capacitor is charged to energy levels higher than or equal to the threshold energy level. This implies that the potential difference across the electrodes of the PPT is large enough to pull the free electrons released from the spark plug. This results in a discharge.

2) The spark plug pulsates at a rate such that it generates free electrons, sufficient in number and of sufficient energy level to move from one electrode to the other, thereby generating a discharge between the gap of the PPT.

In the subcritical frequency region, the increase in the pulse frequency of the spark plug is accompanied by a decrease in the pulse width. Because the voltage input to the spark plug is kept constant, a decrease in pulse width results in a decrease in the total power output of the spark plug. This implies that free electrons generated by the spark plug would be fewer in number and would have a relatively lower energy content. Thus, the potential difference across the electrodes of the PPT needs to be higher so that it can draw the free electrons from the spark plug to initiate a discharge. Therefore, the capacitor needs to be charged to a higher voltage. Because all other circuit parameters were kept constant, the characteristic time for capacitor charging did not vary with pulse width. Therefore, the time required to charge the capacitor to the required discharge potential increases, causing an increase in the discharge time interval. Hence, the discharge frequency decreases.

In the supercritical frequency domain, as the pulse frequency increases, the chances of the total energy content of the system, that is, the sum of the spark energy and the potential difference across the PPT electrodes, being higher than the threshold energy level at a particular instant are higher. This implies that the electrodes could get a sufficient number of free electrons for the required energy level, even if the potential difference across the electrodes is relatively lower, causing PPT discharge at a lower potential difference across the electrodes. Therefore, the capacitor will need to be charged to a lower voltage level to have a PPT discharge. Because of the fixed characteristic charging time of the capacitor, this leads to a lower charging duration and subsequent discharge, causing an increase in the discharge frequency. At a very high pulse frequency, the change in the energy output of the spark plug with the pulse frequency is negligibly small. Thus, the number of free electrons released by the spark plug is almost constant. Therefore, the energy levels at which the free electrons tend to flow between the gap is constant, and, hence, the discharge frequency is not affected much and tends to attain a limiting value.

The critical frequency is the spark plug pulsating frequency at which the discharge frequency of the PPT is at a minimum. This can be attributed to the fact that at this frequency the system posses the disadvantages of both the subcritical and supercritical frequency regions. The system is neither working at such a low spark plug frequency that it can have a large pulse width and, hence, high power output from the spark plug, nor it is working at such a high spark plug frequency that the total energy content of the system crosses the threshold value. Therefore, the disadvantages add up to give the lowest discharge frequency of the PPT.

From the results, it can be concluded that a continuously working spark plug will be the best suited for high discharge frequency of the PPT. However, this will lead to erosion of the spark plug, which will limit the overall life of the PPT.[14] It was also observed that the same PPT discharge frequency could be obtained for two spark plug frequencies, one in the subcritical and other in the supercritical regimes. It is better to work in the supercritical frequency domain where the spark plug pulsation frequency is higher. In the supercritical region, the discharge frequency of the PPT can be modulated in a range by varying the spark plug frequency.

When the pulsation of the spark plug is varied, the discharge frequency of the PPT can be modulated, and, hence, the time-averaged thrust that is provided by the PPT can be controlled. This method of discharge frequency modulation is less complex than the one involving the use of a bank of a capacitor and a high-voltage power supply. It also leads to a reduction in the mass of the system because the need for the bank of the capacitor does not exist.

Effect of Igniter Plug Voltage Input on PPT Discharge Frequency

It was observed that the PPT discharge frequency has no direct dependence on the input voltage of the spark plug, as shown in Fig. 6. This points to the fact that the function of the spark plug in the PPT is to provide a large supply of free electrons with sufficient energy that can lead to a discharge between the electrode plates. There may exist a particular cutoff energy level for the spark plug at which the free electrons with sufficient energy are generated by the spark plug. The energy possessed by the free electrons thus generated will not affect the discharge initiation as long as their energy level is beyond the threshold energy level. Thus, the input voltage to the spark plug, which affects the power (or energy) output of the spark plug, does not play a dominant role in discharge initiation and, hence, does not affect the discharge frequency. However, this holds only if the voltage levels are higher than the cutoff values. The input voltage levels at which the experiments have been conducted might be higher than the cutoff value of the spark plug, and, hence, the discharge frequency of the PPT does not depend on the input voltage. Thus, the only operational parameter of the spark plug that controls the discharge frequency of the PPT is the pulsating frequency of the spark plug.

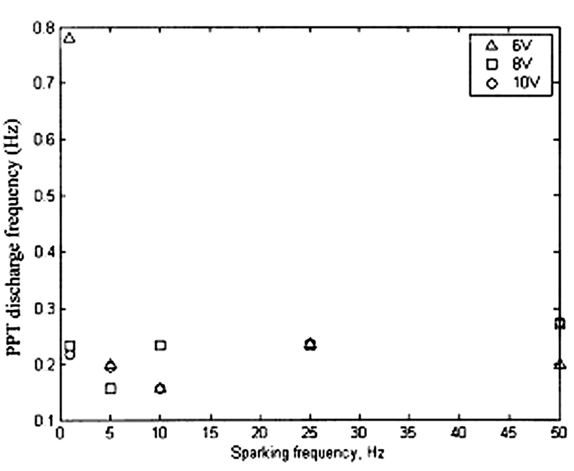


Fig. 6 Effect of spark plug's input voltage on discharge frequency of PPT.

Conclusions

The effect of the igniter plug frequency and its input voltage on the discharge frequency of a solid propellant PPT was studied. It was found that the driving forces that govern the discharge frequency of the PPT are the charging time of the capacitor to the threshold energy level and the energy output of the spark plug. It was observed that there exists a critical frequency of the spark plug pulsation, on either side of which the nature of the dependence of the PPT discharge frequency on the spark plug pulse frequency changes. The minimum discharge frequency of the PPT was found to be at the critical frequency. In the subcritical frequency domain, the discharge frequency decreased with the increase in the pulsation frequency of the spark plug. In the subcritical frequency domain, the governing parameter was the pulse frequency of the spark plug (or the energy output of the spark plug). In the supercritical frequency domain, the discharge frequency increased with the increase in the pulse frequency of the spark plug. Here, the governing parameter is the time that a capacitor takes to charge to the threshold energy level. The discharge frequency was found to be independent of the input voltage of the spark plug. This kind of dependence of the discharge frequency of the PPT on the spark plug pulsation can be found useful in achieving a range of thrust levels from the PPT that is needed for better controllability and maneuverability of the spacecraft.

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