Pulsed Plasma Thruster Systems for Spacecraft Attitude Control

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Abstract

Pulsed Plasma Thrusters (PPTs) are finding renewed user appeal due to the growth in small satellite applications. PPTs are especially well suited to small satellite applications because they are simple, low-mass, and high Isp propulsion systems. The solid Teflon fuel allows for a self-contained, inert and stable propellant system. With a power draw of only 0.1 to 150 W and a very small (50 - 800 μN-s) impulse bit, PPT technology makes it possible to consider a revolutionary attitude control system (ACS) concept providing stabilization and pointing accuracies previously obtainable only with reaction wheels, with reduced mass and power requirements. NASA Lewis Research Center (LeRC) and Olin Aerospace Company (OAC) are working together to develop an advanced PPT system with twice the total impulse capability and half the mass of the previous best PPT system.

The two key factors to accomplish these goals are: 1)significantly improving thrust efficiency - the ratio of thrust power to input electrical power and 2) improving the energy density and life of the energy storage capacitor. Typically, PPTs provide relatively low efficiency, with the LES 8/9 PPT delivering a little more than 7 percent. OAC has tested a matrix of configuration parameters with improvement in the efficiency by a factor of 1.5 to 2.0. To achieve the LeRC goals, the capacitor must be capable of 20 million pulses at an energy level of 40 J, ideally with a mass of no more than 1 kg. LeRC and OAC have embarked upon a two-step process to demonstrate the capacitor technology, with benchtop testing at OAC and integrated PPT/capacitor life testing at LeRC to be conducted in the development phase. The program provides for design, fabrication and qualification of a flight PPT, which is then slated to fly as an orbit raising demonstration aboard the Air Force Phillips Lab MightySat II.1 in early 1999. A second unit, configured for ACS functions, is planned for flight on the NASA New Millennium EO-1 spacecraft in mid-1999.

With a light, high performance PPT in development for flight applications, it becomes possible to consider replacement of momentum wheels with PPTs. Typical momentum wheel attitude control systems consume 10's of W power and weigh 0.1 kg per kg of spacecraft weight, including the momentum desaturation devices. Mission analysis to be presented shows the PPT to be very competitive with these systems, with the advantages of lower cost, lower mass, extension of ACS capability to very small (nano) satellites, and simplicity in replacing both the wheels and the desaturation devices.

Introduction

Attitude control of modern three-axis stabilized spacecraft is performed by systems consisting typically of wheels which absorb torque and momentum and some means of allowing the wheels to slow their rotation rate, either magnetic torquers or thrusters. However, it is well known that this function can also be performed by all-thruster systems.[1] The main reason that it is not commonly done involves the smallest impulse-bit which the thruster systems are capable of generating. Impulse-bit (Ibit) is the product of the thrust of the thruster times the minimum thrust pulse time. Traditional chemical thruster Ibit is limited by the opening and closing time of the valve which controls propellant flow through the thruster. Table 1 shows typical minimum Ibit values for various thrusters.

Table 1
Minimum Ibit Characteristics of ACSThrusters

Thruster	Thrust (N)	Valve cycle duration (s)	Ibit (mN-s)
Monopropellant	0.448	0.012	5.34
Bipropellant	5.0	0.02	100
Cold Gas	0.05	0.010	0.5
PPT		N/A	< 0.1

Recent advances in electric thruster systems are changing the way an all-thruster system is viewed. Pulsed plasma thrusters (PPTs) are electric thrusters with very short duration pulses (~ 5 μs) and very low minimum Ibit (< 0.1 mN-s). PPTs also operate at high specific impulse (> 1000 s). These characteristics make PPTs an attractive option for attitude control system (ACS) functions. The capabilities of PPTs to perform these functions are examined in this paper.

The PPT is shown schematically in Figure 1. The only moving part is the fuel bar which is pushed into the discharge region by a spring. An energy storage capacitor provides the electrical energy for the plasma discharge. Once the Teflon fuel is ablated and ionized by the arc, it is accelerated between the rail electrodes by a j x B, or Lorentz, body force. Figure 2 illustrates the physics of the PPT discharge and acceleration process.

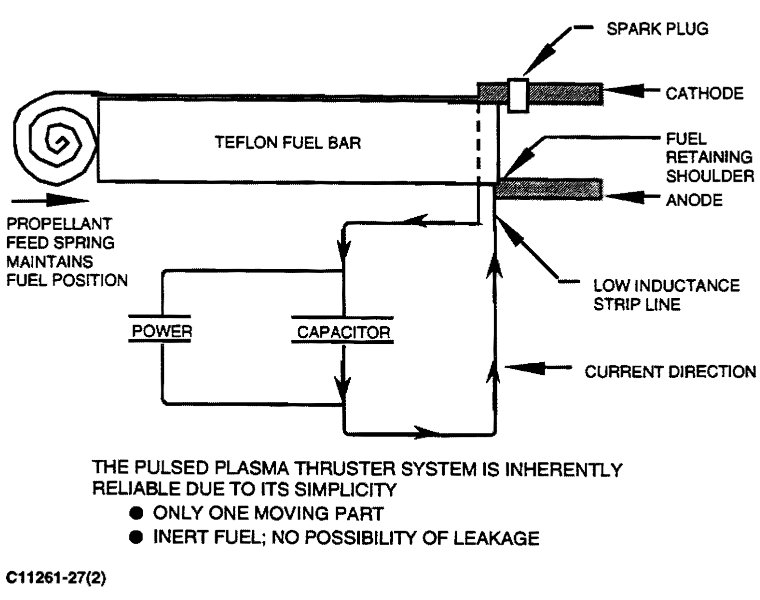

Figure 1 Schematic Representation of a PPT System

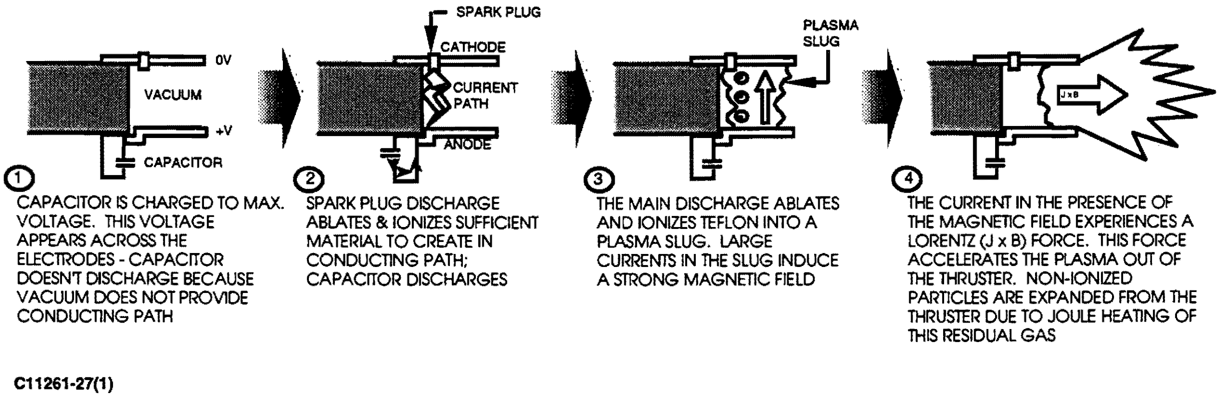

Figure 2 Lorentz Force Acceleration Process in the PPT

The mass advantage of the PPT system derives from its high specific impulse capability. The PPT achieves its high specific impulse by using electrical energy from the spacecraft power bus. While other electric propulsion devices, such as the resistojet, arcjet, ion, and Hall thrusters are also capable of improved specific impulse, they require much more power than most small satellite power system sources can provide, and are much more complex. Operational PPTs have ranged in power from 6 to 30 W, however, for ACS applications, the PPT operates at an average power of less than 1 W.

The PPT is extremely flexible and can easily be customized to meet propulsion requirements for a wide variety of missions. Referring to Figure 1, a thruster is defined as the anode and cathode electrodes, spark plug, and fuel bar with its associated housing and feed spring. Multiple thrusters can be grouped around a single energy storage capacitor and power processing electronics. Thrust and specific impulse in the PPT are both proportional to the energy per pulse, and thrust scales linearly with available power (pulsing frequency).[2] Thrust can also be increased at the expense of specific impulse by increasing the exposed Teflon surface area. The wide range of specific impulse and thrust levels already demonstrated by PPTs illustrate the flexibility of the basic design. Additionally, the simplicity of the PPT results in a very competitive and reliable system. The use of solid Teflon propellant eliminates the need for expensive propellant feed system components such as tanks, valves, and heaters, as well as the safety requirements associated with liquid propellants. Qualification requirements do not have to include pressure vessel tests as do fluid based systems, and because a simple negator spring drives the sole moving part (the Teflon propellant), it is a very reliable system. The system can be built and assembled fully fueled and placed on the shelf for an indefinite period until needed.

To date, the primary operational role for PPTs has been final orbit insertion and drag make-up on the Navy's TIP/NOVA navigation satellites, accumulating over 50 million pulses in 20 years of successful flight operation.[3] The TIP/NOVA PPTs provided extremely accurate and reliable impulse bits which enabled the satellites to provide very accurate ephemeris data. The PPT thrusters allowed correction of disturbances down to 10^{-11} g. The last of these satellites was retired in 1994 with the PPTs were still fully functional. In addition to these flight programs, PPTs have been fully flight qualified for the LES 8/9 and SMS spacecraft. Table 2 lists the successful qualification and flight programs.

Table 2
Pulsed Plasma Thruster Design Features for Flight or Flight Qualified Designs

Parameter	Unit	LES 6	SMS	LES 8/9	TIP/NOVA
Ibit, (Thrust @ 1 Hz)	μ Newton - second	26.7	111	300	400
Specific Impulse	Seconds	312	505	1000	543
Thrust to Power	μN/Watt	10.6	12.2	12	13.3
Capacitor Energy	Joules	1.85	8.4	20	20
Total Impulse	N-Sec	320	1779	5560	2450
Life	Pulses	12,000,000	13,000,000	18,500,000	10,000,000
Mission		East-West Stationkeeping	Attitude Control	Attitude Control	Orbit Insertion & drag make-up

The first flight of the PPT solely to demonstrate the concept of all-thruster ACS will come in 1999 aboard the NASA EO-1 spacecraft. EO-1 is a New Millennium Program (NMP) mission run by NASA Goddard Space Flight Center. It will be the first Earth orbiting NMP mission. The main payload is an advanced Earth imager and the science objective of the mission is to fly in formation with Landsat, 15 minutes ahead or behind, and image Earth resources. The spacecraft weighs approximately 150 kg and has a bus power of approximately 300 W. The PPT will be flown in a back-up mode for a reaction wheel assembly in one of the three spacecraft axes. At pre-determined times during the mission, the wheel in this axis will be turned off and the PPT will be used to maintain stability.

Pulsed Plasma Thruster Attitude Control

This section describes the benefits of using PPTs in attitude control applications for a variety of missions, specifically disturbance torque compensation and completion of slew maneuvers in small spacecraft, and precise pointing of spacecraft.

Attitude Control for a Small Spacecraft in Low Earth Orbit

In an analysis of the attitude control of a small satellite in LEO, PPT systems were found to offer significant mass benefits over momentum wheel systems. The assumptions of this analysis were as follows:

- 50 - 300 kg spacecraft
- 400 km circular orbit, 0° inclination
- Disturbance torques per orbit (all N-m):
    - Solar Pressure = 1.9×10^{-6}
    - Aerodynamic = 8.7×10^{-5}
    - Gravity Gradient = 3.9×10^{-7}
    - Magnetic Field = 2.6×10^{-5}

      Total = 1.1×10^{-4}
- 5 year mission life

Several different PPTs were evaluated, including the LES 8/9 PPT, and three variations of advanced PPTs which are more similar to the thruster that is currently under development. The characteristics of the PPTs used in this analysis are summarized in Table 3. The dry mass of the LES 8/9 PPTs using three thrusters about a shared capacitor is assumed to be 6.43 kg. For the near term advanced technology thrusters having Isp 1000 to 1500 sec, the dry mass for the same configuration is assumed to be 2.07 kg and 2.58 kg respectively. The next generation advanced PPT with a higher Isp of 2000 sec is assumed to have a dry mass of 6.43 kg for the same configuration.

Table 3
Characteristics of PPT systems used for ACS analysis

	LES 8/9	Advanced I	Advanced II	Advanced III
Fueled System Mass, kg	7.2	3.6	3.6	7.2
Total Impulse, N-s	7,500	15,000	15,000	15,000
Impulse Bit, μN-s	298	578	578	578
Isp, sec	1000	1000	1500	2000
Efficiency, %	7	12	14	16

For the PPT system, twelve thrusters are assumed for full control and full system redundancy. The thrusters are grouped in sets of three around a shared energy storage system. This configuration required four PPT systems for the full three-axis ACS. Both the momentum wheels, and the PPT systems were sized to counter the total disturbance torque environment. The PPT systems were scaled by the amount of propellant required for compensation against the disturbance impulses, thus the variation as a function of disturbance torque between the different PPT systems is a result of the different assumed specific impulses.

The baseline momentum wheel system used in this analysis is assumed to have four wheels, and six hydrazine desaturation thrusters. The hydrazine thruster system is sized for an assumed total impulse of 10,000 N-s, which is consistent with the baseline of a 100 kg spacecraft with a 1.7 m^2 cross sectional area. The desaturation system assumptions do not include tank and feed system component masses, making the momentum wheel system mass somewhat optimistic. The baseline disk radius is 0.08 m, and the wheel speed is 3000 rpm. The breakdown of the momentum wheel system masses is given in Table 4.

Table 4
Baseline Momentum Wheel System Mass Breakdown

Component	Unit Mass (kg)	# of Units	Total Mass (kg)
Individual spinning mass	3.6	4	14.4
Drive electronics	0.91	4	3.64
Structure	2.0	1	2.0
Four wheel system mass			20.04
dumping thruster dry mass	0.4	6	2.4
200 s Isp Propellant mass	5.23	N/A	5.23
six thruster 200 Isp mass			7.63
dumping thruster dry mass	0.4	6	2.4
280 s Isp propellant mass	3.73	N/A	3.73
six thruster 280 Isp mass			6.13

The effect of varying spacecraft mass (at constant area) and increasing array area (at constant spacecraft mass) on the mass of the attitude control system were evaluated for both momentum wheels and PPTs. Spacecraft mass does not influence the levels of the environmental disturbance torques as much as a change in spacecraft cross-sectional area for the baseline configuration. Increase in power requires an increase in solar array area, which in turn results in higher solar pressure and atmospheric drag contributions. Other factors such as a change in spacecraft geometry from the addition of antennae, booms, etc., can also contribute to an increase in cross-sectional area. For the purpose of this study, the spacecraft bus was simplified and only the arrays significantly change the cross-sectional area. Both of these comparisons scaled the attitude control systems for the average total disturbance torque compensation for the entire five year mission of the spacecraft. The momentum wheel system mass increases as the physical size of the spinning mass increases to absorb the increased disturbance momentum. In the PPT system, an increase in momentum translates to an increase in propellant and thrust time. The results of this evaluation are shown in Figures 3 and 4. Although the PPT system masses appear constant there is a small variation in total mass due to the required additional propellant as the disturbance torque increases.

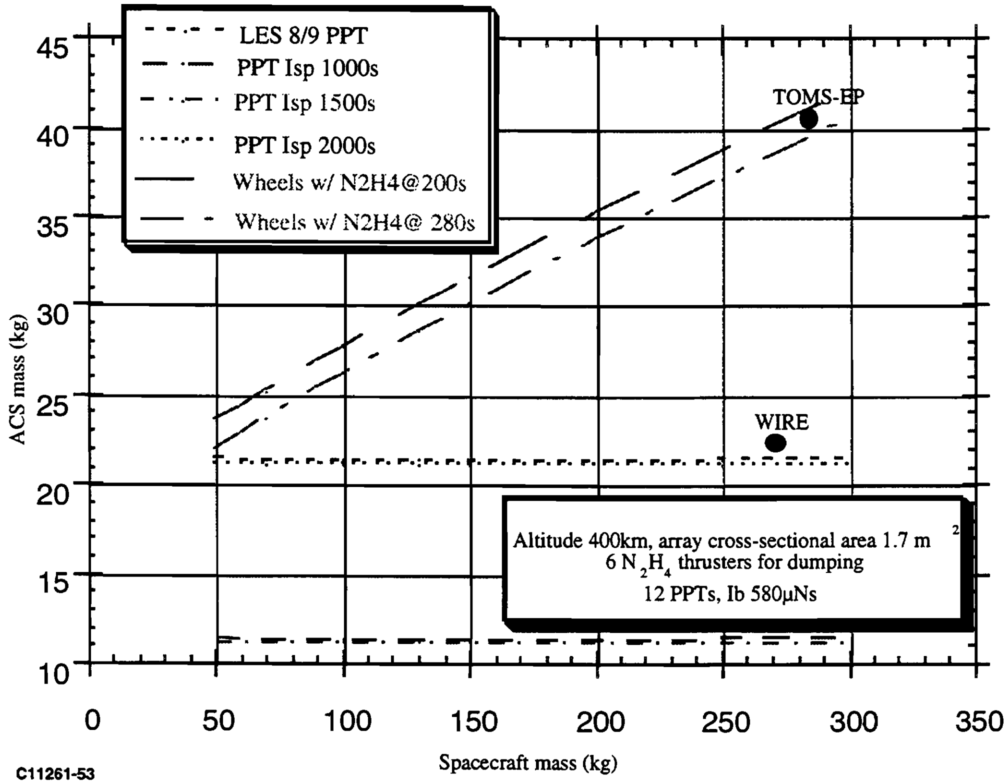

Figure 3, Attitude Control System Mass for Varying Spacecraft Mass

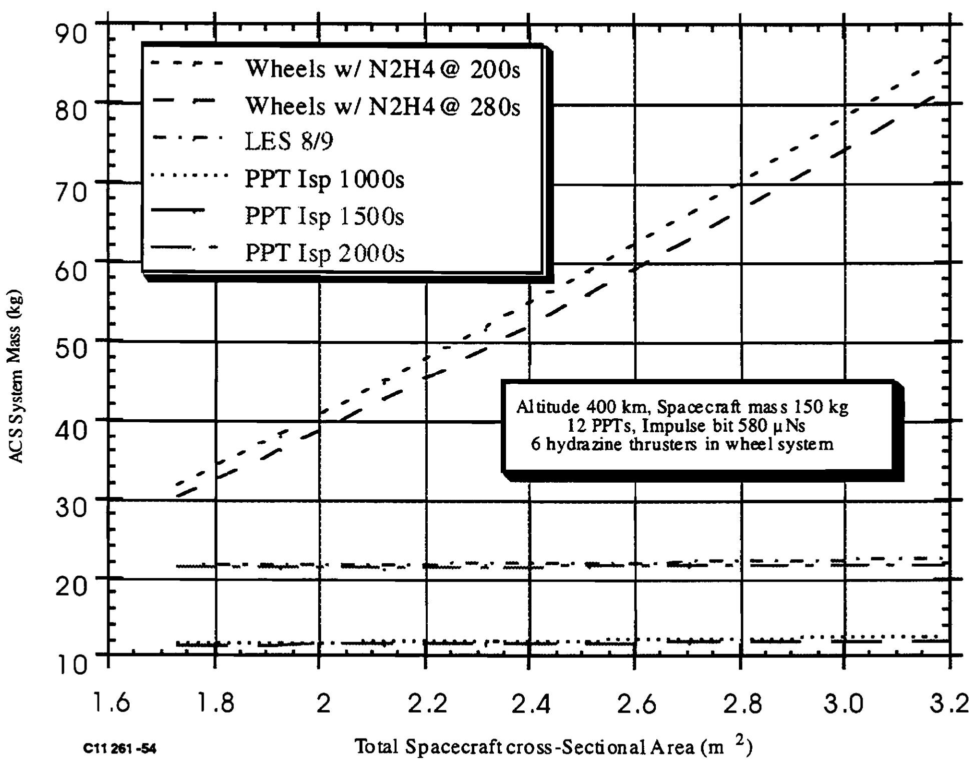

Figure 4, Attitude Control System Mass for Varying Spacecraft Cross-sectional Area.

In both cases, the PPT systems provide the same attitude control for significantly less mass. It can be seen in Figures 3 and 4 that the PPT attitude control system (12 kg) for disturbance torque compensation is 50% to 25% of the mass of the momentum wheel system (20-40 kg) for varying spacecraft mass. In the case of varying spacecraft cross-sectional area, the PPT ACS mass is 50% to 12% of the mass of the momentum wheel system (20-80 kg). While the momentum wheels only absorb cyclical torques, the PPTs are used to cancel out all disturbances, both the cyclical (magnetic, atmospheric, gravity gradient), and secular torques (solar pressure). All torques are factored in to the total disturbance torques used in the above evaluation. For these applications, the PPTs would be required to fire once every one to two minutes, for a total required number of pulses of $1.5\text{x}\ 10^6$ to $3.18\ \text{x}10^6$ depending on the system used. The average power required for the PPT systems is between 0.18 and 0.37 W depending on which PPT system was assumed.

Slewing Maneuvers

Another function of the PPT ACS that was evaluated for this spacecraft is a 360° slewing maneuver. For slewing maneuvers in which a large angular rotation to the vehicle is required, the required PPT power levels increase as the required maneuver time decreases. Power level is a function of pulse rate. Figure 5 shows the time required for this maneuver for the three advanced PPTs from Table 3. The spacecraft assumptions include a moment arm of 0.5 m, and moment of inertia (I_{cm}) of 80 kg-m^2.

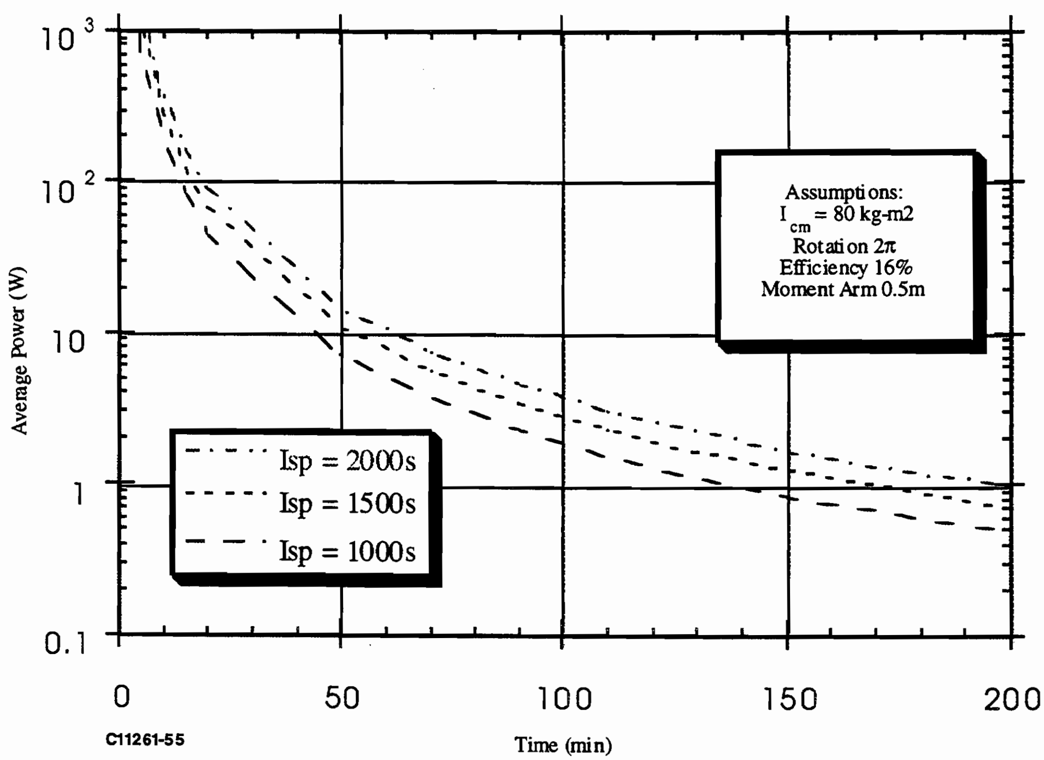

Figure 5, Required Power Levels for PPT System Slewing Maneuver Times

The power averaged over the entire maneuver duration is solved independent of pulse rate or impulse bit for these calculations, and is solely a function of time required for the maneuver. The following equation shows power as a function of maneuver time.

$$\text{Pavg} = \frac{\theta \cdot Isp \cdot g \cdot Icm}{\eta \cdot L \cdot (\Delta T)^2}$$

Here, θ is the slew maneuver angle, I_{sp} is the specific impulse of the PPT, g is the gravitational constant, I_{cm} is the moment of inertia of the spacecraft, η is the efficiency of the thruster system, L is the moment arm, and ΔT is the maneuver time. Therefore, a θ of 2π is a worst case slew maneuver, and smaller angles will result in smaller average power requirements.

In the case of the complete rotation, as the time constraint is reduced, a larger torque is needed and therefore the PPT must provide either a higher impulse bit or higher pulse rate. Each of these increases results in a higher average power for the PPT system. The result is illustrated in Figure 5 for a complete 360° spacecraft rotation. For maneuver time requirements of less than 10 minutes, average power levels are 200 W and greater. However, if the maneuver time is allowed to be approximately one half the orbit (~ 50 minutes), the average power levels drop to 10 W and lower. Also, these power levels only need to be sustained during the slew maneuver and could be supplied from batteries. From Figure 5 it can be seen that the shorter the required maneuver time, the higher the power requirement from the PPT system becomes. For maneuvers that must be performed in a minute, the PPT power reaches 10,000 W, making the PPT system a practical impossibility for such maneuvers. However, if the maneuver times can be relaxed to periods similar to orbital periods, PPT systems become attractive for this application.

Precise Pointing Applications

The small impulse bit of the PPT enables spacecraft pointing control to an extent that exceeds the resolution of state-of-the-art current rate sensors. This small impulse bit allows keeps the spacecraft within its deadband target for a greater length of time between firings, thus reducing chatter, and enabling very precise pointing of the spacecraft. Nominal time between firings is 1 to 3 minutes. The deadband angular spacecraft drift between pulses is between 0.03° and 0.014° depending on assumed performance and pulse frequency. Higher frequencies will result in smaller deadband angles, but also in higher average power levels. For example, for a 100 kg spacecraft, a pulse frequency of 0.05 Hz results in average power during firing of 0.9 W, where a frequency of 3 Hz results in a average power of 54.8 W. Therefore, the power consumption of the PPT system is a function of the demands of the mission.

Another measure of the flexibility of the PPT system is that the Ibit can be changed on-orbit by simply varying the charging time of the capacitor. In this way, operating the capacitor at differing stored energies, a range of Ibits can be achieved, allowing tailoring of the Ibit to the required function.

Conclusions

PPT systems now under development offer an interesting alternative for ACS of small satellites. Studies have shown the PPT system to be capable of replacing momentum wheel-based systems with no loss of capability, except possibly rapid slewing. PPT systems offer the benefits of lower mass, reduced power consumption, and smaller physical size when compared to a wheel-based system. In addition, PPTs have no rotating components and thus provide a jitter-free environment between pulses, minimizing concern over possible impacts to sensor optics. Cost of a PPT system is also expected to be less than half the cost of a typical wheel-based system.

Potential concerns to users, such as contamination of spacecraft surfaces and EMI are being addressed in the development program. A series of ground tests are underway at NASA LeRC and flight tests on the AF Mightysat are planned to address the concern of contamination. [4 5] Ground testing is also planned to verify that the PPT system will meet MIL-STD 461 EMI requirements. These issues, as well as standard integration issues such as thermal and structural/vibration interfaces, will be addressed for both Mightysat and EO-1.

The PPT system is also uniquely able to perform both ACS functions and limited ΔV translation functions. When considered for such dual-use roles, the mass and cost advantages are even greater.

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