Space Vehicle Power System Comprised of Battery/Capacitor Combinations

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Abstract

Recent improvements in energy densities of batteries open the possibility of using electric rather that hydraulic actuators in space vehicle systems. However, the systems usually require short-duration, high-power pulses. This power profile requires the battery system to be sized to meet the power requirements rather than stored energy requirements, often resulting in a large and inefficient energy storage system. Similar transient power applications have used a combination of two or more disparate energy storage technologies. For instance, placing a capacitor and a battery side-by-side combines the high energy density of a battery with the high power performance of a capacitor and thus can create a lighter and more compact system.

A parametric study was performed to identify favorable scenarios for using capacitors. System designs were then carried out using equivalent circuit models developed for five commercial electrochemical capacitor products. Capacitors were sized to satisfy peak power levels and consequently "leveled" the power requirement of the battery, which can then be sized to meet system energy requirements. Simulation results clearly differentiate the performance offered by available capacitor products for the space vehicle applications.

Introduction

"Aside from the main engines and solid rockets, the single highest-risk equipment on the space shuttle are the auxiliary power units, generators that power the shuttle's hydraulics. Today, those generators use a highly volatile and toxic rocket fuel", as quoted from NASA's Shuttle Web site.

The space shuttle orbiter uses conventional hydraulic actuators for all flight control surfaces. Although the shuttle's actuators have been exceptionally reliable during flight, experience has demonstrated that launch vehicle hydraulic systems are troublesome during ground servicing and testing for the following reasons:

1) The hydraulic components are highly susceptible to contamination. Procedures for maintaining cleanliness during assembly and test operations are expensive and time consuming.
2) The system is susceptible to leaks at component interfaces and dynamic seals. A leak anywhere in the system necessitates reservicing the entire system.

For these reasons, a conventional hydraulic system will not meet NASA's future cost and performance goals. A survey of advanced actuation technologies has determined that the two most promising technologies are electromechanical actuators (EMA) and electrohydrostatic actuators (EHA). The power system will need to supply high peak power to drive the tens- to –hundred plus horsepower range of electromechanical and electrohydrostatic actuators.

Clear benefits can be derived by incorporating more than one technology to power a load with a widely fluctuating demand. A fast response storage device,

for example a capacitor, is effective in delivering short pulses, but it generally has low energy density and thus must be physically large to meet energy needs. A slow response storage device, for example a battery, has much higher energy density but it generally is not effective in delivering short pulses and likewise must be physically large to meet power needs.

Some preliminary high discharge rate testing of Lithium Ion battery cells indicates that 10C or larger discharge rates are possible. These data would lead to the consideration of a smaller overall battery. However, a further consideration in this area is the effect of the high discharge rates on the cycle life of the battery at the depth of discharge in the application. The minimum desired bus voltage at End of Mission will determine the depth of discharge allowed for the battery. Since the actuators are a constant power load often a combined system can more optimally meet both energy and power requirements and thus form a smaller and lighter solution than either technology alone and also eliminate high discharge rate concerns on the life of the battery. The benefits of combining batteries and capacitors has been evaluated for both electric vehicles and wireless communication applications.[1,2]

For this study we determined the size capacitor system required to supply power above baseline for load profiles associated with thrust vector control, flight surface control, pre-launch loads, ascent, and descent for the three reusable space transportation system vehicles. This methodology allows design of the power system that more closely meets the exact energy and power demands. Capacitor response is predicted using equivalent circuit models derived for several candidate capacitors selected from products available commercially or in pilot production.

Electrochemical Capacitors

Electrochemical capacitors (ECs), also known as double-layer capacitors, supercapacitors, or ultracapacitors, store electrical energy by means of charge separation at an electrode interface. ECs have higher energy density than other types of capacitors and are therefore strong candidates for power load-leveling in space applications. ECs have additional attractive features of high cycle life, high reliability, long life, and they require no maintenance. In contrast with batteries, they do not rely on chemical reactions and, thus, have better low temperature performance and are inherently safer.

NASA incorporated ECs into a hybrid electric transit bus to load level power requirements during acceleration as well as to recover energy during braking. They found ECs allowed the engine size to be reduced significantly for some vehicles and drive cycles.[3,4]

Commercial electrochemical capacitors are available in small sizes for the computer and telecommunications industry applications and in large sizes for automotive applications. A number of the larger commercial ECs have been described[5] and their performance reported.[6] For this study we examined the energy and power characteristics of five large commercially available electrochemical capacitors. The properties of these ECs are listed in Table 1.

Table 1 – Properties of the electrochemical capacitors cells examined in this study.

Capac-itor	Rated Capaci-tance(F)	Rated Voltage (V)
A	2,500	2.5
B	2,000	2.3
C	130,000	1.6
D	5,000	2.7
E	3,200	2.5

Trade Studies

System performance was examined for a variety of mission and power system scenarios. This was done using SPICE-based modeling and a method similar to that described by Billerbeck and Lewis.[7] The power system elements include a constant-current bus, the load power profiles, and the electrochemical capacitor. The system constraints are listed below.

Assumptions and Constraints

System assumptions and constraints for the trade studies are as follows:

- Load voltage must remain in the range of 250 V – 280 V. Bus current of 150 A
- The capacitor only satisfies power requirements above the baseline value.
- No regenerative energy capture.

Assumed requirements for the voltage are as specified in MIL STD 704E which allows the voltage to drop below 250 V for short periods. However, we used 250 V as the lower limit for these studies.

Capacitor Model

The electrical response of most ECs cannot be accurately described by a series-RC circuit. This is especially true at higher power levels and is due to the porous material that comprises the electrodes of these capacitors. Resistance and capacitance are distributed and the electrical response mimics that of a transmission line.

In this study, in most cases, capacitor performance was modeled using a five-time-constant model. This type of model has been used previously for ECs and is accurate over a wide range of conditions.[8] These models were developed for five candidate capacitors using electrochemical impedance spectroscopy (EIS) data.[9] The data were fit using the method of Boukamp.[10] The model for capacitor cell A is shown in Figure 1.
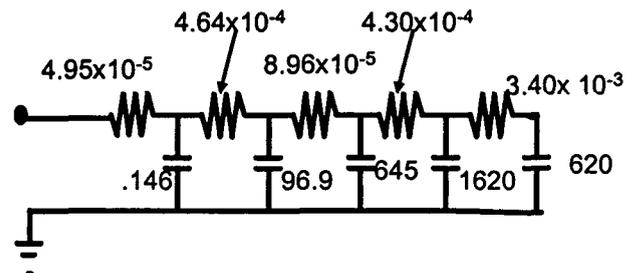
Figure 1 – Equivalent circuit model for capacitor cell A. Resistance values are in ohms, capacitor elements are in Farads.

A multiple-time-constant model was selected for three reasons. First, a ladder network physically mimics the distributed nature of the charge stored in a porous electrode; second, it can be easily combined with various load or battery models and used for circuit analysis; and third, it generally provides an excellent fit to the test data. Thus, each capacitor is represented by a five-time-constant circuit,

not a single time constant circuit. Then the first capacitor is the fastest element to discharge, with a time-constant of R1xC1, and the last element is the slowest to discharge, with a time-constant of (R1+R2+R3+R4+R5)xC5.

Capacitor technology C is a capacitor designed for traction applications and has a very long response time, much greater than the pulse widths of features in the load profiles of the space vehicles. For this capacitor a simple RC circuit model was adequate.

Scaling Cell Equivalent Circuit Models to 280 V Modules

Most manufacturers of electrochemical capacitors offer only single cell units rated at 2.3 to 2.7 V, although some commercial devices are available as multicell modules rated to 14.2 V or higher. The present application requires a capacitor operating at 280 V. To satisfy this voltage requirement, many cells must be connected in series. And to meet the energy requirements, multiple series-connected strings are connected in parallel. For this study, partial capacitors and partial strings of capacitors were allowed, although this is not physically possible. In practice, single cell capacitor implementation using these commercial devices is envisioned to be similar to that described for NiCd batteries in the X-38 Crew Return Vehicle.[11]

The time response of a 280 V, full size capacitor module assembled by connecting cells in series and parallel is the same as the time response of an individual constituent cell. Capacitance and resistance for the module are related to single cell values using standard rules for adding components in series and parallel.

The equivalent circuit for the full scale module was derived first to meet the 280 V requirement. For n cells rated at V_r connected in series to yield a 280 V string, the capacitance, resistance, and mass are:

$$C_S = \frac{C_c}{n}$$
$$R_S = nR_c$$
$$M_S = nM_c$$

where the subscript S denotes string and C denotes cell.

For m strings connected in parallel to create a complete module, the capacitance, resistance, and mass are:

$$C_T = mC_S$$
$$R_T = \frac{R_S}{m}$$
$$M_T = mM_S$$

where the subscript T denotes the total module.

Additional mass associated with cell voltage derating[12,13] for series connected capacitors and active or passive voltage balance system are not included. Likewise cell interconnections and packaging are not included.

Power Profiles

Hypothetical load power profiles were constructed for each vehicle. These power profiles are based on potential architectures for NASA's Second Generation Reusable Launch Vehicle Program. Depending on the vehicle, the power draw included any or all of the following: warm-up and testing (pre-mission), engine start, actuators that move the thrust vector control gimbals, and actuators that move the flight control surfaces. The booster and orbiter, which have engines, include all of these features, while the power profile for the CTV, without an engine, includes only testing and use of the motorized flight control surfaces. Engine start, which requires very high energy, was excluded from the hypothetical power profiles used for this study. These power profiles represent potential worst case power transients in all other aspects.

The power profile was separated into steady state and transient components. Batteries or fuel cells were assumed to be the power source to meet baseline requirements and capacitors were assumed to be the power source for transient power requirements.

Transient power profiles for each vehicle during each phase of the mission are shown with the modeling results. Duty cycles were specified to be ~15% but the modeling studies were done using duty cycles of 30 – 50%. These higher duty cycles did not require larger capacitors because recharging from the 150 A bus was very fast. Similarly, because of fast capacitor recharge, there is no difference in the size capacitor required for a nominal mission and an aborted mission.

Two system architectures were examined, a centralized and distributed design. The former used a single capacitor to meet transient power requirements while the latter had separate capacitor modules for each component of the transient load.

Capacitor Sizes for Booster, Orbiter, and CTV Loads - Centralized Systems

A hypothetical transient power profile (above baseline) for a booster mission is shown in Figure 2. The large pre-launch peak is the power required to concurrently test the actuators on the gimbals of all five engines. The ascent phase includes engine gimballing at three different power levels. The descent includes pulses for engine gimballing and actuation of flight control surfaces. The large peak at the end of the descent represents engine gimballing in preparation for landing.
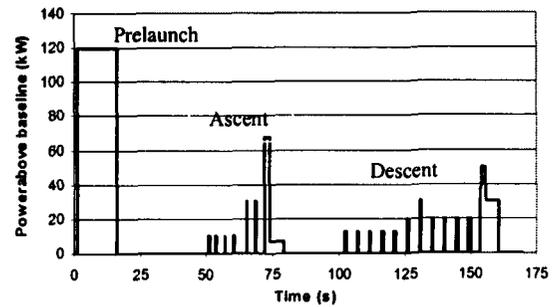
Figure 2 – Hypothetical transient power profile for a booster mission.

It was convenient in this study to reduce the times between pre-launch and ascent, and between ascent and descent phases of the mission to about 30 s. This time compression did not effect the outcome because of the fast recharge of the capacitor. Thus, the times between phases of the mission have no effect on capacitor sizing.

The voltage response of capacitor A to the hypothetical booster mission power profile of Figure 2 is shown in Figure 3. The capacitor, initially charged to 280 V was sized to exactly maintain the voltage above 250 V.

Since the 120 kW pre-launch feature requires a large quantity of energy at high power, the capacitor size required to meet this feature is significantly oversized for all other features in the power profile. Voltage drop was less than 3 V during the ascent and descent portions of the mission.
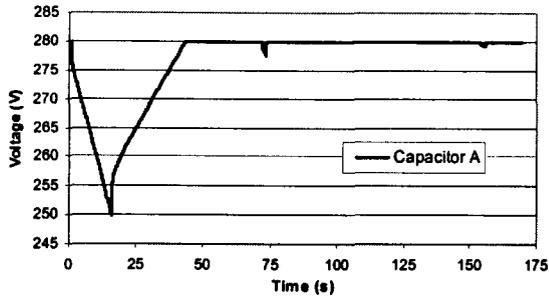
Figure 3 – Capacitor response to booster power profile shown in Figure 2. Capacitor is sized so the voltage does not drop below 250 V.

Simulation results for type A cells that meet the power requirements for the pre-launch load have a mass of 550 kg and a volume of 460 liters. The capacitor recharge after power delivery for the pre-launch load is sufficiently fast to make it available for ascent and descent phases of the mission.

The hypothetical transient power profile and the resultant response of type B cells for an orbiter mission are shown in Figure 4. The power profile is similar to that of the booster mission, but with lower power levels because the orbiter has three engines versus five engines for the booster.

Again the pre-launch feature determines the capacitor size required but the capacitor sized for the pre-launch is not as oversized as in the booster. A 160 kg, 130 liter capacitor module of type B is required to supply the specified load and maintain the voltage within the 280 V to 250 V window.
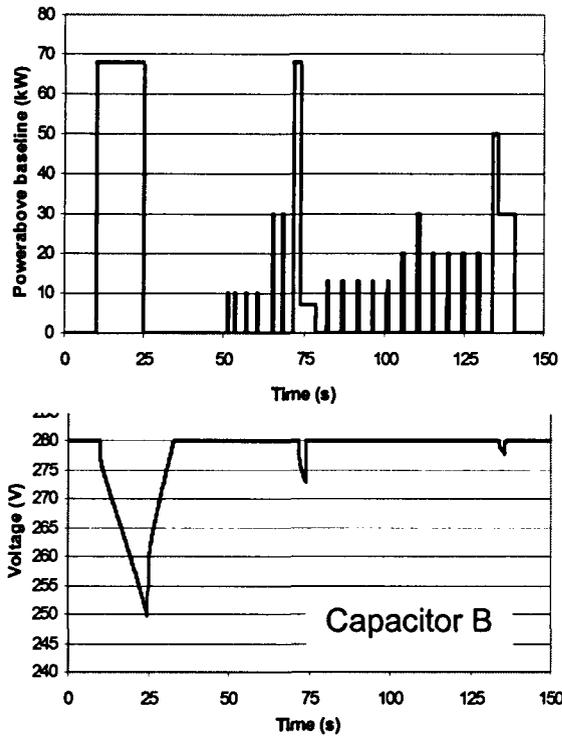
Figure 4 – Hypothetical power profile and capacitor response for an orbiter mission.

The hypothetical transient power profile (above background) and capacitor type A response for a CTV mission are shown in Figure 5. The load has four large peaks representing one pre-launch test of all flight control surfaces and three pre-descent tests of all flight control surfaces. Again, because of fast capacitor recharge, the time between these peaks in the simulation has been compressed to less than 25 seconds between pre-launch and pre-descent tests for convenience. This had no effect on capacitor sizing. During an actual mission the time between launch and descent may be as long as 20 days. Again the pre-launch feature determines the size capacitor required: 60 kg and 50 liter for capacitor module comprised of type A cells.
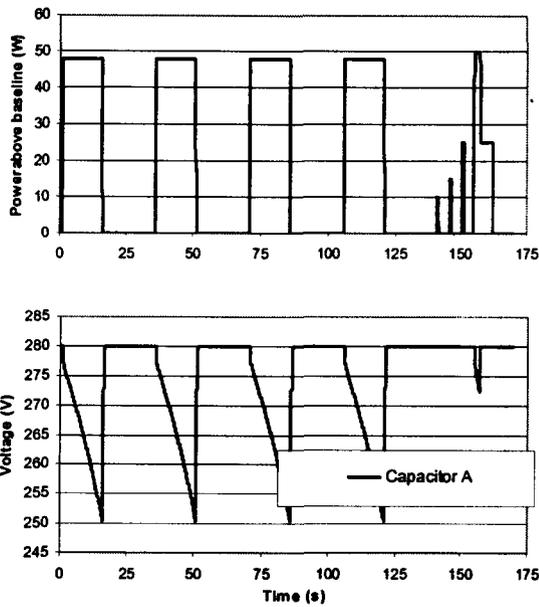
Figure 5 – Hypothetical power profile and capacitor response for a CTV mission.

Simulation results for the different vehicles and capacitor types are listed in Table 2. The differences in mass and volume reflect the power and energy performance differences among the capacitor types.

Capacitor technology E yields the lowest-mass system for the booster, capacitors B, D, and E have the same minimum values for the orbiter, and capacitor B has the minimum for the CTV.

Table 2 –Capacitor size required to meet the power profiles shown in Figures 2, 4, and 6.

Capaci-tor type	Booster		Orbiter		CTV	
	Mass (kg)	Vol-ume (l)	Mass (kg)	Vol-ume (l)	Mass (kg)	Vol-ume (l)
A	550	460	200	160	60	50
B	480	380	160	130	46	40
C	890	340	180	120	52	36
D	450	370	160	130	50	41
E	440	350	160	120	48	38

Capacitor Sizes for Alternate Booster Power Profile

The modeling and simulation approach described permits different mission scenarios and power system architectures to be investigated.

One scenario investigated was a booster profile with sequential rather than concurrent testing of the five engine thrust control actuators. In this scenario, the load was assumed to be a series of 120 kW pulses lasting 0.2 s and separated by 0.8 – 1.8 s of lower power draw, as shown in Figure 6. While the peak power is the same for both pre-launch scenarios, the total energy required for the sequential test profile is only 9% of that required for the concurrent test.
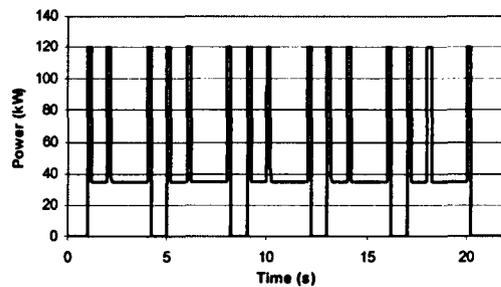
Figure 6 – Alternate power profile for the booster pre-launch test.

Physically, the sequence of pulses shown in Figure 6 corresponds to 1) high initial power draw to overcome static friction, 2) lower power draw as the engine gimbal traverses from the center position to one limit, 3) a second large pulse to reverse the gimbal direction, 4) low power draw as the gimbal traverses its full range to the opposite limit, 5) a third large pulse to reverse gimbal direction again to return the engine to its center position, and 6) no power draw until the next engine thrust vector controller is tested with the same sequence.

The response of one of the capacitor types to this alternate power profile is shown in

Figure 7. The capacitor size (type C) required to provide concurrent power for this scenario is less than half that required for the power profile shown in Figure 2. The size reduction is even more significant for a lower energy/higher power capacitor such as capacitor type A which can be more fully recharged between the 120 kW pulses. The response of capacitor type A is shown in Figure 8.
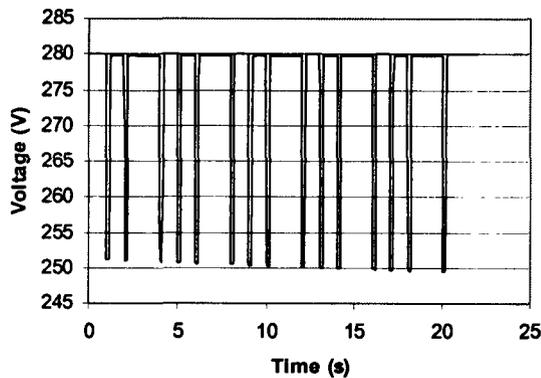
Figure 7 –Capacitor C response for the booster power profile with sequential test of the five engine actuators.
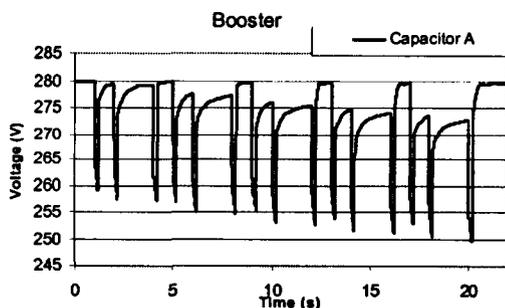
Figure 8 – Capacitor A response for the booster power profile shown in Figure 6 with sequential test of the five engine actuators.

Simulation results for each of the five capacitor types are summarized in Table 3. The mass and volume reductions obtained from the alternate pre-launch test is different for each type of capacitor, depending on its

performance match to the load profile. Capacitor technology E formed the minimum mass solution with concurrent pre-launch engine tests. It was 2% lower than the second best capacitor type. Capacitor technology B was the minimum mass solution for the sequential testing. It was 29% lower than the second best contender.

Table 3 – Capacitor size for different pre-launch scenarios.

	Pre-launch Engine Test Concurrent		Pre-launch Engine Test Sequential	
Capaci-tor type	Mass (kg)	Volume (l)	Mass (kg)	Volume (l)
A	550	460	110	67
B	480	380	55	48
C	890	340	380	270
D	450	370	140	110
E	440	350	78	62

Decentralized

The second system architecture examined was a decentralized power system. One scenario utilizes capacitors only for flight control surfaces. An example is shown in Tables 4 and 5 and Figure 9. This power profile is a subset of that shown in Figures 2 and 4 and is to the same for both the booster and orbiter vehicle.

Table 4 – Size capacitor required to power only the flight control surfaces compared to the size required for the complete booster load profile.

	Flight Control Surfaces Only of Booster Load		Complete Booster Load	
Capaci-tor type	Mass (kg)	Volume (l)	Mass (kg)	Volume (l)
A	110	84	550	460

Table 5 – Size capacitor required to power only the flight control surfaces compared to the size required for the complete orbiter load profile.

	Flight Control Surfaces Only of Orbiter Load		Complete Orbiter Load	
Capacitor type	Mass (kg)	Volume (l)	Mass (kg)	Volume (l)
A	110	84	200	160

The type A capacitor module for the flight control surfaces is 110 kg and 84 liters versus a 550 kg, 460 liter module required for the complete booster power profile or a 200 kg, 160 liter module required for the complete orbiter power load.
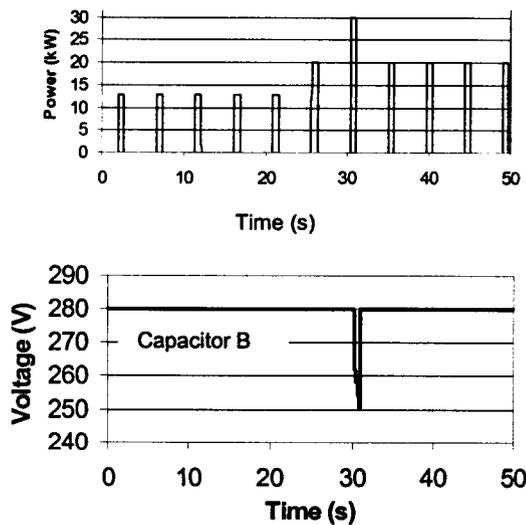
Figure 9 – Power profile and capacitor response for booster flight control surfaces only.

Discussion

The capacitor can provide power for the short, high-power pulses above the baseline energy requirements of the vehicle. But it is not a net producer of energy. It must be used with a primary energy source, i.e.

battery or fuel cell. The combination can create a more optimum power system, one having lower mass than from use of a single technology.

Based on these SPICE-based circuit simulations, the size capacitor module required for different segments of the power profile ranged from 46 to 440 kg and 40 to 350 liters depending on the vehicle, power load, and how the power is managed. For the reported power profiles, capacitor type B appears to be best suited. Other factors including reliability, efficiency, and cell-to-cell variability will play a role in capacitor selection. This last factor is important since large variability in cell properties may required significant voltage derating.

Smaller capacitor modules would be possible if the voltage window were larger. For example, the energy stored by a capacitor in the window 280 V to 175 V is three times the energy stored in the 280 V to 250 V window. Thus capacitor sizes would be reduced to about one third if the lower voltage limit were set at 175 V instead of 250 V. However, a voltage window increase can adversely impact motor and actuator sizes. Consequently, multiple factors must be considered to create the optimum system.

Conclusions

Equivalent circuit models of five commercial capacitors were derived and scaled to meet the transient portions of hypothetical reusable space transportation system power profiles. The volumes and masses of the scaled capacitor systems were strongly dependent on the technology. Some technologies were clearly more suited for this application than others. For instance, among the power profiles examined, the ratio of maximum to minimum capacitor mass for the five technologies was a factor of 6.9. The ratio of maximum to minimum capacitor volume for the five technologies was a factor of 5.6. Even greater ratios may arise when manufacturing dependent

factors such as cell voltage derating are included.

The methodology described allows quick examination of various system architectures, potentially leading to the most optimum solution. It offers flexibility in that changes in the power profile or operating voltage window can be quickly incorporated and simulated. And finally, it provides insight into what type of changes in capacitor and actuator technology might offer further system mass reductions.

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