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Chemical Double-Layer Capacitor Power Source for Electromechanical Thrust Vector Control Actuator

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Power sources for electrical actuation systems need to be made as compact as possible for many potential applications. Size and weight constraints require that the energy and power densities of the source be as large as possible. While, in general, it is not possible to optimize both these parameters simultaneously, chemical double-layer (CDL) capacitor technology offers an excellent combination of the desirable energy and power density characteristics required in a source for these applications. The work presented here focuses on the design, testing, and evaluation of the CDL capacitor technology in combination with batteries as a unique power source for electrical actuation systems. In this research effort CDL capacitor technology was applied in the design and development of a power source for thrust vector control electromechanical actuators currently being developed for use on the Space Shuttle's solid rocket boosters. CDL capacitors have many properties that make them well suited for actuator applications. Among them are that they have the highest demonstrated energy density for capacitive storage (about a factor of 5–10 less than NiCd batteries), have power densities up to 50 times greater than NiCd batteries, are capable of 500,000 charge–discharge cycles, can be charged at extremely high rates, and have nonexplosive failure modes. Thus, CDL capacitors exhibit a combination of desirable battery and capacitor characteristics.

Introduction

AMONG recent developments within the R&D community is the trend whereby more traditional hydraulic actuation systems are being converted to electrical actuation systems. The motivating factors are numerous and include increased reliability, reduced environmental impact, reduction in expensive ground tests and maintenance, reduced costs, and lighter weight systems. Also, there is a multiagency program to, in general, develop more electric systems for a variety of applications entitled the More Electric Initiative. With respect to electric actuation, the technology has matured with improved electric components, power processors, and high-energy density–high-power density sources.

Electrical actuator systems are being pursued as alternatives to hydraulic systems to reduce maintenance time, weight, and costs while increasing reliability. Additionally, safety and environmental hazards associated with the hydraulic fluids can be eliminated. For most actuation systems, the actuation process is typically pulsed with high peak–power requirements, but with relatively modest average power levels. The power–time requirements for electrical actuators are characteristic of pulsed power technologies where the prime source is sized for the average power levels while an intermediate store provides the capability to achieve the peak requirements. Among the options for the power source are battery systems, capacitor systems or battery-capacitor hybrid systems. Battery technologies are energy dense but deficient in power density; capacitor technologies are power dense but limited by energy density. The battery-capacitor hybrid system uses the battery to supply the average power and the capacitor to meet the peak demands. This hybrid system typically results in a smaller, more efficient system.

Chemical double-layer (CDL) capacitors exhibit a combination of desirable battery and capacitor characteristics, and they have many properties that make them well suited for actuator applications. They have the highest demonstrated energy density for capacitive storage (about a factor of 5–10 less than NiCd batteries), have power densities up to 50 times greater than NiCd batteries, are capable of 500,000 charge–discharge cycles, can be charged at extremely high rates, and have nonexplosive failure modes.[1–4] Ongoing research efforts are investigating the application of CDL capacitor technology as primary power sources for electric vehicles and magnetic field experiments as well as for backup systems for motors, actuators, valves, and lighting systems.[1,4,5]

The results described in this article consist of the construction of an experimental 270-V full-power capacitor bank system using off-the-shelf, commercial CDL capacitor technology and the evaluation of its ability to perform electrical actuation typical of that needed for the Space Shuttle thrust vector control. This bank is not optimum for either energy density or power density, but is adequate to demonstrate the technology.

Background

In 1887, Helmholtz discovered that the interface between a conductor and a liquid electrolyte formed a layer capable of storing charge. For strong electrolytes, this layer is estimated to be only a few angstroms thick.[6] Because of the fact that there are materials with surface areas greater than 1000 m^2/g, it is possible to produce practical capacitors with the surface area/interface thickness ratio on the order of the inverse of the permittivity of free space. This results in capacitors with a capacitance greater than 1 F in a volume on the order of a dime. This technology was first pursued to practice by SOHIO[7] and NEC,[8] and there are a considerable number of units commercially available for low-voltage, high-imped-

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Table 1 Capacitor technology

Parameter	Electrolytic	CDL SOA	CDL Near-SOA	Film–foil–paper–oil
Energy density				
W-h/kg	0.55	2.0	5	0.55
W-h/liter	0.55	3.9	8	0.55
Mode	Polar	Bipolar	Bipolar	Bipolar
Voltage	600 V/unit	1.2–3	1.2–3	5 kV/pad
Frequency response	Good	Low	Low	Excellent
Scaling	Linear	Linear	Linear	Linear
ESR	2–10 mΩ/unit	2–10 mΩ/cell	2–10 mΩ/cell	<1 mΩ
Capacitance range	μF–F	mF–multi F	mF–multi F	μF
Shelf life	10–20 year	10–20 year	10–20 year	Indefinite

ance applications. Typically, the large surface area material utilized in these devices is some form of carbon or a rare-Earth oxide. There are also a number of electrolytes (both aqueous and organic) available for use in these capacitors, with the ultimate choice being governed by the application. In general, the use of organic electrolytes increases energy storage density at the expense of internal resistance and power density.

Table 1 shows the approximate state of the art (SOA) in advanced capacitor technology contrasting conventional technologies such as electrolytics and the common high-voltage film–foil–paper–oil units. Referring to Table 1, CDL technology is almost a factor of 10 more energy dense than the best conventional capacitor technologies that might be employed for electric actuation. In contrast to electrolytics, the CDL capacitors are bipolar and do not require conditioning. To achieve high-energy density, the film–foil–paper–oil capacitors must work at voltages much higher than that desirable for most actuator applications. CDL capacitors, while having low voltages per unit cell, are readily constructed into multicell stacks to achieve operating voltages in the range of 100–500 V, which is ideal for most actuator applications.

A CDL capacitor consists of two beds of high surface area materials separated by a porous membrane. The entire assembly is immersed in a suitable electrolyte. The construction, assembly, and theory of operation of CDL capacitors can be found in the literature.[6,9–11] Materials such as the activated carbons are highly fractionated with enormous surface area as a result of the pore structure. The large surface area materials most often used in the double-layer capacitor technologies are ruthenium oxides and carbons such as carbon black. In general, the carbons have the highest surface areas, with commercially available materials having surface areas greater than 2000 m^2/g. Surface areas of this magnitude are only achievable with a highly porous structure with average pore dimensions of only a few angstroms in diameter. For example, specification sheets from commercial sources for activated carbon state that the surface area is about 1500 m^2/g with a mean pore dimension of 22 Å. Since pores with dimensions on the order of twice the double-layer thickness or less cannot be used to store charge, much of the surface area is not accessible in any finished device.[6] Further, it is necessary for the electrolyte to penetrate the pore in order that a conducting path be available to the external circuit. Consequently, the resistance from each micropore to the external circuit is dependent upon its size and position with the carbon bed. Thus, a tradeoff exists between the surface area and the pore dimensions for a particular application.

Figure 1 is an approximate circuit diagram for a CDL. Starting at the top of the figure, the resistance R_{ext} is the resistance associated with the external circuit (load and diagnostics) and is under the control of the experimenter. Since the total capacitance of the array is the sum of the capacitance of numerous tiny pores (of differing values) in parallel, it is instructive to qualitatively examine how the array is structured. Since there is mirror symmetry in the unit, it is sufficient

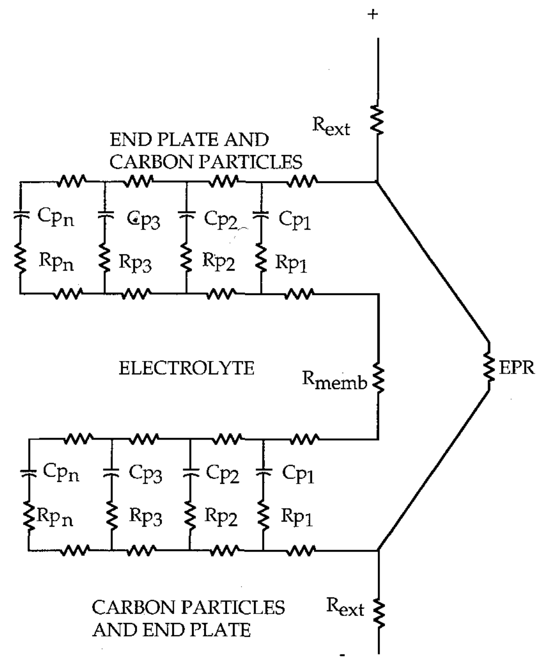

Fig. 1 Approximate circuit diagram for a CDL capacitor.

to examine the electrical pathways only to the membrane. For a given pore, there is the resistance associated with the current-carrying path through the metallic end plate/metallic fibers and through the fiber/grains of carbon. In a porous bed with many fibers/grains tightly packed, there are a number of current-carrying paths of various resistances possible from any given pore. The value of the resistance associated with that path is a function of the packing parameters, pressure, resistivity of the bed material, resistivity of the metallic end plates, and position within the bed.

The Helmholtz double layer discussed previously represents the dielectric or energy storage media in the usual sense. Passing through the double layer, the conducting electrolyte in the pore constitutes the other electrode. The specific resistance of a pore will be a function of the diameter and length of the pore and is designated as R_p. Similarly, the electrolyte is distributed throughout the interstices of the bed forming multiple pathways to the porous membrane. The membrane resistance R_{memb} is a function of the porosity of the membrane and is experimentally determined to be essentially the resistivity of the electrolyte times the percent porosity. Note that each pore is connected to its neighbor by shunt resistances that are also functions of the resistivities of the constituents. The net result is that charge can be redistributed during and after a discharge event that does not totally deplete the stored energy. However, this phenomenon is not of particular concern for most of the applications being considered today. It is these resistances, which in sum, determine the equivalent series resistance (ESR) and the equivalent parallel resistance

(EPR) of a given technology. These parameters are important to any given application and were measured in this work.

Numerous electrolytes have been used in the construction of CDL capacitors. Commonly used aqueous electrolytes have been sulfuric acid and potassium hydroxide. The high conductivity of these electrolytes is their most desirable characteristic. Since they are aqueous based, it is necessary to operate each cell of the capacitor at a voltage less than 1.2 V. Further, the corrosive nature of these electrolytes places restrictions on materials that can be used for long-life devices. By contrast, organic electrolytes such as propylene carbonate with lithium and ammonium salts have been operated at voltages as high as 3.5 V in practical devices, but they have electrical resistivities approximately an order of magnitude higher than aqueous electrolytes. Since the energy stored in a capacitor is proportional to the square of the charge voltage, it would appear that organic electrolytes would be desirable, and many commercial devices now employ organic electrolytes. However, the internal resistance of the finished capacitor is usually ohms per square centimeter of unit cell. This high value of internal resistance limits the range of applications.

Experimental Setup

The CDL capacitor power source was designed and the units configured to meet the specifications of the Space Shuttle's solid rocket booster (SRB) thrust vector control (TVC) electromechanical actuators (EMA). The units used in this power system were prototypes available from Panasonic and were rated at 470 F at an operating voltage of 2.3 V. A series arrangement of these units was used to meet the 270-V voltage requirement while providing an ESR that was significantly lower (by about a factor of 10) than the effective impedance of the electromechanical actuator. The power source consisted of the primary energy storage units (CDLs), charging power supply, and associated circuitry contained in a transportable structure.

Our experiments indicated that these units could safely be operated at 2.7 V and, at this voltage, had an average capacitance of 534 F, as will be described later. Once constructed, the developmental energy storage system was evaluated as a potential power source for the SRB TVC EMA by testing its performance into simulated loads. To simulate the motor current profile for the SRB TVC EMA, the initial peak current level during motor startup indicated that initially it looks like a 3-Ω load for approximately 100–200 ms as the motor begins to spin up.[12] Then, it appears as approximately an 18-Ω load for the duration of the 1-s pulse cycle. The circuit used to simulate the actuator is shown in Fig. 2. The control system design for the load simulation allowed for initiating the current discharge into the load, switching between the different load power levels, and subsequently shutting off at the end of the desired cycle time. Repetitive cycling of the system at the various power levels to simulate the actual flight profiles was also incorporated into the system design.

Capacitor Bank

For the capacitor bank to be constructed from commercially available units, each unit had to be tested to ensure that parameters such as capacitance and equivalent series resistance were consistent between units that were to be connected in series. This was necessary to guarantee uniform voltage grading within the capacitor bank and to prevent individual devices from seeing excessive voltage stresses. Thus, 120 units were purchased with the intent of using 112 in the final 300-V capacitor bank assembly.

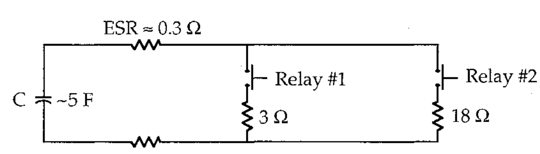

Fig. 2 Actuator simulation test circuit.

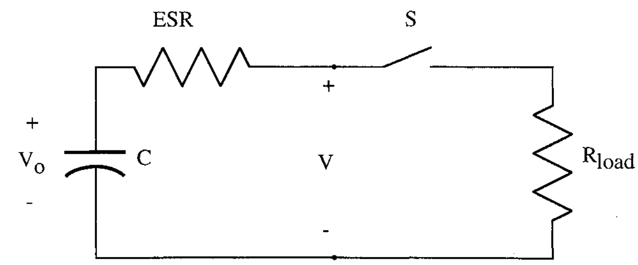

Fig. 3 Test circuit for determining ESR.

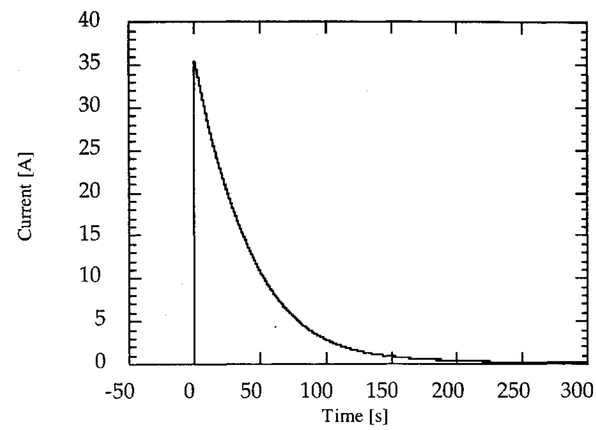

Fig. 4 Typical capacitor discharge waveform.

Capacitance measurements were determined by performing a full discharge of the capacitor into a known resistive load to obtain the current waveform. The test circuit used to characterize the capacitor units is shown in Fig. 3, while Fig. 4 depicts a current waveform from a typical discharge that was used to determine the capacitance as well as to calculate the ESR. The stored charge can then be found by integrating the current waveform over the complete discharge cycle as

$$Q = \int_0^t i \, dt \tag{1}$$

and the capacitance can then be found from

$$C = Q/V \tag{2}$$

The ESR can be found through voltage division from the circuit in Fig. 3. If the capacitor is charged until no current flows, then $V \approx V_0$ before closing the switch S. After closing the switch, voltage division between the load resistance and the ESR is used to determine the ESR. Thus, the initial voltage reading across the load resistor is

$$V = V_0 \left(\frac{R_{\text{load}}}{R_{\text{load}} + \text{ESR}} \right) \tag{3}$$

Then, from Eq. (3), the ESR can be found from

$$\text{ESR} = R_{\text{load}}[(V_0/V) - 1] \tag{4}$$

Each capacitor unit was cylindrical having approximate physical dimensions of 5 in. tall, 2 in. diameter, and weighing 300 g. Using the testing procedures outlined earlier, the average capacitance for these units was found to be 534 ± 15 F. Figure 5 is a histogram of the test data that were taken at a

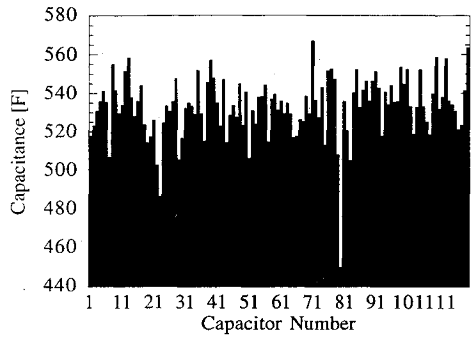

Fig. 5 Histogram plot of the capacitance test data.

charge voltage of 2.7 V. While the capacitance was consistently higher than the nominal value, the most critical parameter was the deviation between units and this was well within acceptable levels for almost all of the devices. The differences between the measured capacitance and the nominal capacitance can be attributed primarily to the testing method used to determine capacitance and perhaps to a voltage dependence of the capacitance. In the tests performed here, a complete discharge of each unit was performed to measure the capacitance. The rated capacitance value was determined by only partially discharging the capacitor,[13] which generally results in a lower numerical value. However, the values obtained from our tests are consistent with those obtained by Burke[4] who was evaluating these capacitors for electric vehicle applications. The ESR was measured to be, on average, 3.25 $\pm$ 0.29 mΩ. Again, the uniformity between units is the most critical parameter. The deviation, measured as described earlier, was within acceptable levels for this particular application.

The equivalent parallel resistance (EPR) is also of interest for actuation applications. The EPR, a measure of the self-discharge characteristics of the unit, was found by charging the capacitor to the desired charge voltage and removing the charging power source. Without switching in a load, the voltage decay of the capacitor was monitored and attributed to the EPR of the capacitor. For applications where the system must be held at the operating voltage for long periods of time, a large EPR is desired such that the voltage droop is minimized during periods of inactivity. For these capacitor units, the EPR was measured for only a few devices, but the EPR was consistently found to be on the order of a kilo-ohm. Thus, assuming an exponential decay, the resistance capacitance (RC) time constant for the self-discharge of a unit is approximately 500,000 s (almost 6 days). This should ensure that the desired operating voltage level could be maintained with minimal trickle charging requirements.

After testing all of the capacitors, 112 selected units were connected in series and assembled into a bank with minimal total system mass, volume, and footprint size. Thus, the bank was constructed with two racks of 56 units stacked on top of each other. The connections between capacitors were made using $\frac{1}{2}$-in.-wide, $\frac{1}{8}$-in.-thick strips cut from sheet copper. Structural support was provided by using phenolic sheets that sandwiched the capacitor array and were screwed together using threaded rods. The final assembly with both capacitor arrays was approximately 15 $\times$ 15 $\times$ 11 in. and weighed approximately 85 lb. The assembled bank had a capacitance of approximately 4.77 F and was designed to operate at 300 V, resulting in an energy storage capacity of approximately 215 kJ. The system was extensively tested into dummy loads (Fig. 2), which accurately represented the load characteristics of the actuator used in this analysis.

Actuator Test Bed Description

The 50-hp actuator used in these tests was the first generation of TVC prototypes designed at NASA Marshall Space Flight Center.[14] The system consists of two 25-hp motors, a gear train, roller screw, and two 27-kW analog controllers. The motors used in the design were three-phase, brushless dc motors. The roller screw, which converts rotational motion to linear motion, was a high-efficiency linear device capable of transmitting high loads with reasonable accuracy. Pulse width modulation techniques are utilized by the 27-kW controllers with insulated gate bipolar transistors, rated at 500 V and 200 A, used in the drive circuitry for the actuator. Current, sensed by a Hall effect device, and position feedback, provided by a resolver at the output of the gear train, were used in the control of the actuator. At the time these tests were performed, only one 25-hp motor and one 27-kW controller were configured for use on the system.

The battery bank used in these tests consisted of 21 deep-cycle, marine lead-acid batteries configured into a 270-V system capable of providing up to 400 A as needed. While this bank does not represent an optimum battery configuration, it does provide a comparison basis for evaluating the performance of the capacitor power source. Also, it gives an indication of how much savings in terms of size, weight, and cost for the total power system can be accomplished when a capacitor source like the one described here is used in conjunction with a battery source.

The electric actuation test facility at Marshall Space Flight Center consists of a hydraulic load bench with the capability to control both the rate and load levels. The load bench is used to validate the performance of TVC actuators for loads up to 100,000 lbf and rates up to 20 in./s. For the testing and evaluation in this research effort, the load levels used were no-load 5000, 10,000, and 15,000 lb.

Results

The test bed diagnostics used for the evaluation of the CDL capacitor source are shown schematically in Fig. 6. The current sensors I1, I2, and I3 are used to monitor the battery current, capacitor current, and total current, respectively. The battery, capacitor, and total voltage levels were also monitored and are denoted by V_b, V_c, and V_t, respectively.

The actuator was operated using three different power source configurations. First, to establish the baseline operating conditions for the actuator system, it was operated using only the battery bank as the power source since this was the standard operating mode for this actuator in the test bed. Second, only the capacitor bank was used to power the actuator to compare the performance of the system with that of the previous case. Third, the capacitor and battery were both connected into the system and the system performance again monitored. Parameters of interest during these tests were the capacitor voltage, capacitor current, battery voltage, and battery current levels as well as the number of actuation cycles that could be performed before the voltage level dropped below the minimum desired operating threshold of approximately 235 V.

Battery-Only Tests

The first set of tests performed consisted of powering the actuator with only the battery source. This was done to establish the power levels required by the actuator under certain load conditions. A typical current waveform for this test is shown in Fig. 7 for the case where the actuator load was approximately 10,000 lb. As can be seen in the figure, the peak current drawn by the actuator was between 65–70 A.

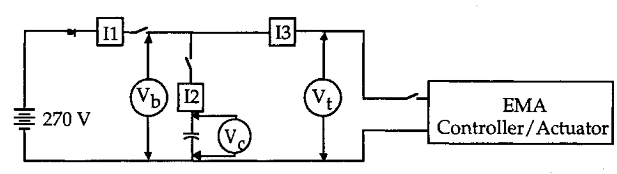

Fig. 6 Test setup schematic.

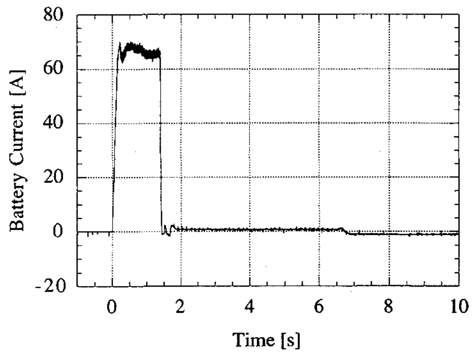

Fig. 7 Current waveform for battery-only test for 10,000-lb load.

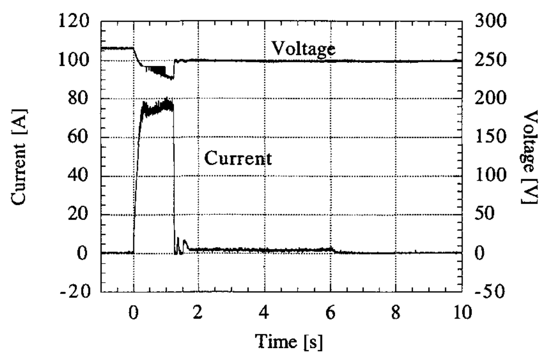

Fig. 8 Current and voltage waveforms for capacitor-only test for 10,000-lb load.

Capacitor-Only Tests

After determining the actuator performance using the battery power source, the test was repeated with only the capacitor bank connected to the actuator. The resulting current and voltage waveforms are shown in Fig. 8. The peak current drawn from the capacitor power source was approximately 70 A, with the current waveform in Fig. 8 essentially the same as for the battery case in Fig. 7. The purpose of this test was to demonstrate the capability of the capacitor power source and to verify the sizing and design of the system. The energy efficiency of the capacitor bank was determined by forming the ratio of the energy delivered to the load to the total energy dissipated during the pulse. From the waveforms in Fig. 8, the energy delivered to the load was found from integrating the voltage–current product to be approximately 23 kJ. The integral of the $i^2 \cdot$ESR product shows that approximately 2.5 kJ was lost due to the internal resistance of the capacitor bank. Thus, the efficiency for the transfer of stored energy to the load approaches 90% for this capacitor bank in this test configuration.

Battery/Capacitor Hybrid Tests

After performing load tests for both the capacitor bank and the battery bank separately, the two power sources were connected in parallel for a series of tests. Figure 9 shows the current contribution from each of the sources for the same 10,000-lb load test that was used for the individual tests. Figure 9a shows the capacitor bank current waveform, whereas Fig. 9b depicts the contribution from the battery. The portion of the capacitor current waveform that goes negative results from current being delivered from the battery source and going to recharge the capacitor bank. Note that the battery now only needs to supply a peak current of approximately 15–20 A compared to the 65–70-A levels shown in Fig. 7. Thus, the addition of the capacitor bank into the power train for the actuator significantly reduces the requirements for the battery source, which was sized more for power than the requisite energy.

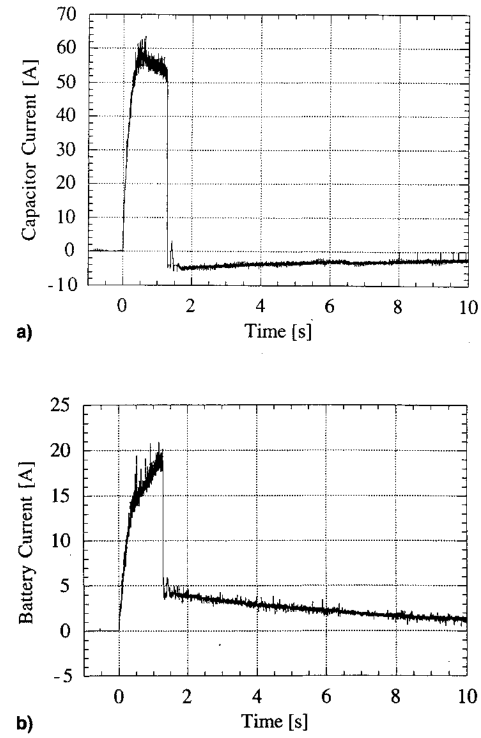

Fig. 9 a) Capacitor current and b) battery current for battery/capacitor hybrid test for 10,000-lb load.

Also of interest is the voltage swing that occurs during the actuation cycle. For the case of the battery only and under a 15,000-lb load, the actuator voltage dropped from an initial value of 260 V down to approximately 164 V. With the battery/capacitor combination power system, the voltage drop during the actuation cycle was reduced significantly as the voltage dropped only to 235 V. The smaller voltage swing during the actuation process reduces device stresses in the controller circuitry and allows for better control of the system.

The real benefits of the capacitor bank can be realized when sizing a complete power source to meet the demands of this actuator as tested. For the complete power source for a space flight application, the battery chemistry of choice would be silver–zinc (Ag–Zn) based on past flight history, off-the-shelf availability, and it's minimal voltage sag observed in pulsed load application testing done in-house at NASA–MSFC.[15–17] For comparison purposes in battery sizing, we limit the rate at which the battery will be discharged to no greater than a 1-C discharge rate (coulomb rate is determined by battery capacity units per hour, i.e., a 1-C rate for a 10-A-h battery would be 10 A). From the test data for the battery-only tests, a battery would need to be rated at least an 80-A-h capacity. A full 270-V, 80-A-h Ag–Zn battery would weigh approximately 450 lb based on the manufacturer's data sheet for a 180-cell battery. Likewise, sizing a battery for the battery-capacitor hybrid configuration based on the corresponding test data would require a 20-A-h capacity. A full 270-V, 20-A-h Ag–Zn battery (180 cells) would weigh approximately 100 lb. To arrive at a total power source weight for the hybrid configuration requires adding the weight of the capacitor bank (approximately 85 lb) to the 100-lb battery weight, yielding a total weight of 185 lb. A weight comparison of the battery/capacitor source to the battery-only source shows a power source weight savings realization of 59% for the hybrid source.

Table 2 is a listing of rechargeable battery technology. If the lithium polymer battery technology matures, further savings in weight would be realized.

Table 2 Rechargeable battery technology

Parameter	NiCd	Lithium polymer SOA	Lithium polymer Near SOA	Lead acid	Silver–zinc Primary	Silver–zinc Secondary	Alkaline nonrechargeable
Energy density							
W-h/kg	40	160	300	35	110	100	95
W-h/liter	90	265	600	100	200	185	210
Power density							
W/kg	700	115	300	70	658	559	40
W/liter	1575	210	600	210	1234	1049	88
Cell voltage, V	1.2	3	3	2.2	1.5	1.5	1.5
Self discharge	20–50	0.1	0.1	10–20	3	2	0.5
Number of cycles	1000	>150	>1000	400–600	N/A	200	None
Operating temperature, °C	−10 to 50	−20 to 70	−40 to 125	0 to 100	10 to 50	0 to 45	−20 to 55
Memory effect	Yes	None	None	None	N/A	None	None

Conclusions

Chemical double-layer capacitor technology offers several advantages when considered a primary element of the power train for electromechanical actuator applications. The combination of a CDL capacitor bank and an appropriate battery technology results in significant weight savings for the total system power source. For this TVC actuator application, the addition of the capacitor source enabled the battery sized for the power source to be reduced from 450 to 100 lb. Such mass reductions are enabling and necessary if electric actuation is to be competitive with hydraulics. Further reductions in mass and volume (~factor of 2), both for the capacitor and battery, will result if current research efforts are successful and units can be custom designed for a specific application such as TVC. It is obvious from the previous discussion that CDL capacitors are designer devices and minimum volume and mass units can only be designed within a system context and within the framework of space-qualified components. The capacitor units offer advantageous lifetime characteristics in terms of the large number of charge/discharge cycles that can be performed. Further, they have been shown to perform predictably and exhibit good thermal stability over a wide temperature range. Since commercially available units have reasonably consistent capacitance and ESR values, it is easy to design a laboratory nonoptimum power source for a particular application by connecting units in series to achieve the desired operating voltage level and to parallel units to reduce the ESR.

Key technology issues related to the design, development, and construction of custom units for this application have been identified. Critical parameters identified for further study include packaging and technology issues such as size, geometry, weight, scaling laws, and temperature dependence of relevant parameters.

Acknowledgments

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