JOURNAL OF AIRCRAFT
Vol. 44, No. 6, November–December 2007

Engineering Notes

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Specific Weight: A Challenge for a Fuel-Cell-Powered Electric Helicopter

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DOI: 10.2514/1.28898

Nomenclature

a	=	equivalent distance from the shaft of the lever at which the extra weight is applied
b	=	distance between the lever-scales contact point and the center of the lever
c	=	minimum distance between the shaft of the helicopter and the shaft of the lever
d_i	=	distance from the shaft of the lever at which F_i is applied
F_h	=	lifting force of the helicopter
F_i	=	any of the forces applied to the lever system
F_s	=	contact force between the scales and the lever
I_{in}	=	input current to the Hall-effect sensor
K_1, K_2, K_3	=	constants
V_{out}	=	output current of the Hall-effect sensor
$V_{\mathrm{out}(I=0)}$	=	output current of the Hall-effect sensor when there is no input current
W_h	=	weight of the helicopter
W_w	=	weight of the auxiliary weight placed on the lever
$\bar{X}$	=	mean value of the magnitude X

Received 22 November 2006; revision received 11 July 2007; accepted for publication 14 July 2007.

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Introduction

HERE the specific weight or weight/power ratio will be used for the weight divided by power. In this section fuel-cell-powered vehicles, and specifically helicopters, are described, focusing on the cost and specific weight of their fuel cells. In addition, the specific weight of different fuel cells is shown.

Fuel cells are a promising option to power different kinds of vehicles [1]. Fuel-cell-powered vehicles have been extensively analyzed, in cost and/or functionality, under different experimental conditions. Under base-case conditions, fuel-cell cars have higher global costs than conventional cars, but they have the lowest externality costs (externalities are indirect effects, traditionally not considered in the costs, such as environmental and health effects). They have the lowest global costs if they are mass produced and externalities are highly valued [2].

Some fuel cells have been specially designed for helicopters created to fly on Mars [3]. The helicopter’s fuel cell displays an acceptable weight/power ratio of about 0.944 g/W. However, the fuel cell costs 400, 000 U.S./kW. This value is higher than the usual ones for fuel cells (5000 U.S./kW) and is not affordable for most conventional applications.

Fuel-cell systems can provide much energy per unit of mass (thousands of W · h per kilogram), with limited explosion risks [4]. Therefore, they can be an interesting option for aircraft.

Although the main problem for the fuel cell is its high cost, weight is also an important parameter. Here we will focus on the weight/power ratio.

Several aspects of fuel cells, such as the specific weight, are described in [5]. Specific weights have significantly decreased in the last 12 years, from a 6.7 g/W goal, to recently achieved specific weights of 2.5 g/W by NASA, whereas before this a 10 g/W specific weight was about the lower limit for alkaline fuel cells. At that time there was a special design, the monolithic solid oxide fuel cell, which achieved 0.12 g/W. On the other hand, the methanol fuel cell displayed a high specific weight of 143 g/W.

Fuel cells have more energy but less power per unit of mass than batteries or capacitors [6]. Therefore, when higher power is needed for some milliseconds or seconds, capacitors are used, but in helicopters, high power is required during several minutes. This problem could be solved by improving the specific weight of fuel cells. NASA has obtained a specific weight of 5.3 g/W in a whole regenerative fuel-cell system [7].

Specific weight also plays an important role, not only in helicopters, but in all terrestrial vehicles. The feasibility of hybrid vehicles is analyzed in [8]. As reported there, fuel cells need 10 g/W in a continuous regimen to be used with terrestrial vehicles and 3–5 g/W if they are required to provide all the power during the peaks. To achieve these specific weights needed for the peaks, the use of a supercapacitor (with a specific weight of 0.15 g/W) in a fuel-cell-powered train is proposed in [9].

The aim of this work is to analyze whether or not fuel cells are suitable as an unconventional-energy propulsion system to power electric helicopters. To this aim, first the specific-weight requirements of an electric helicopter are determined. Later, the specific-weight values obtained are compared with that of fuel cells currently available.

Helicopter Experiments

The variables measured to obtain the helicopter specific-weight requirements are: helicopter current, voltage, and lifting force (the helicopter current and voltage are the current and voltage supplied to the power electronics of the helicopter, which are mostly used for the rotor movement). Current and voltage are needed to derive the electrical power consumption, and the lifting force is needed to know the maximum weight of the required fuel cell. To measure each variable, a sensor was selected and sensor signals were converted to voltages, which were input into the processing system using an analog-to-digital (A/D) board. The lifting force was obtained by means of a precision scale, using a MATLAB program. Several proprietary boards were designed and built so that the former sensor signals generate a potential difference between a signal terminal and a ground terminal.

Helicopter Data

The helicopter has two main blades. The rotor diameter is 104.1 cm. The helicopter weight is 1100 g and its length is 91.2 cm.

It is powered by a three-phase dc brushless motor (FUN600-17 of Kontronic). The motor can work in temperatures up to 150°C. Its maximum speed and current are 50,000 rev/min and 45 A, respectively. The maximum speed of the motor is 1700 (rev/min)/V. Therefore, at 16 V (the maximum voltage of the tests) its maximum speed is 27,200 rev/min. The motor comes with power electronics. When tested in the helicopter, the motor maximum speed was about 22,000 rev/min (slightly less than the expected speed due to the friction forces in the gears and the blades). Although the motor temperature was not measured, no significant problem due to temperature was observed.

The helicopter has two wood blades. The radius of both blades is 52.05 cm from the rotor axis. The solidity is 0.0590. They are convex on both sides, although they are almost flat on the lower side.

Electrical Measurements

A 2:1 voltage divider was used to measure the voltage. A Hall-effect sensor was used to measure the current, as it gives a voltage output related to the input current. A 5 V computer power source, with a maximum output current of 30 A, was used to feed the current transducer.

Lifting Force Measurement

The lifting force was measured using scales and a lever system. Data are processed through a MATLAB application that opens and closes communication with the scales for each experimental test and measures the force 50 times in each experimental test.

The lever had its center 85 cm over the ground level, to reduce the ground effect. The length of each arm was 63 cm. The contact point with the scales and a small weight were on the extreme end of an arm, whereas the helicopter center was near the middle of the other arm. The friction on the lever system was below 0.07 N · m. This causes an error below 12 g on the scale's measure.

Equilibrium of the moments gives

$$F_h = K_2 \cdot (F_s - K_3) \tag{1}$$

where F_h is the lift force and F_s is the force measured by the scales.

The scales were calibrated at zero for $F_h = 0$, so they really measure $(F_s - K_3)$; K_2 was calculated as

$$K_2 = F_h/(F_s - K_3) \tag{2}$$

using a dynamometer to measure F_h.

Data Acquisition and Visualization

Two different applications were created to acquire and process the sensor data for different variables measured. The first one on Visual Basic to acquire the voltage and current signals. The second one on MATLAB to read the force applied to the scales.

Experimental Test Series

Ten series of experimental tests were performed. Each test is a group of measurements taken under the same voltage and pitch angle. Each series is a set of 19 tests, at different pitch angles and at the same open-circuit voltage called "base voltage." Some series had the same base voltage (16 V), but others had different values, such as 14, 12, 10, and 9 V.

Numerical Algorithms and Data Analysis

A computer algorithm was developed to analyze the three recorded input variables: voltage, current, and lifting force. The aim of this analysis was to calculate the maximum specific weight of a fuel cell required to feed the helicopter, under different conditions (payload, safety). The helicopter was assumed to lift its own weight plus an extra weight, namely payload, such as a video camera. The maximum weight/power ratio will be referred to as the "critical ratio" and it is calculated for each test and series. These calculations were performed for different helicopter + payload weights ranging from 0 to 2500 g, in 100 g intervals. Weights higher than 1100 g (the helicopter weight) mean that a payload is added to the helicopter. Total weights lower than 1100 g simulate lighter helicopters. For each of these total weights, the highest weight/power ratio for the fuel cell among all the tests is the critical ratio.

The mean of every input variable was calculated for each test and series, and so was the standard deviation. The standard deviation of the mean was calculated from the standard deviation of the sample (experimental test).

To have a higher probability of lift exceeding weight, uncertainty must be considered. Uncertainty was considered using the standard deviations. The systematic error was ignored because it was much lower than the nonrepeatability error (the systematic error was always less than 3% of the value of the measured magnitude in the tests with optimal specific weights).

The standard deviations of the variables voltage, current, and lifting force were quadratically combined to calculate the standard deviation of the weight/power ratio (they were assumed to be statistically independent).

The critical weight/power ratio r can be calculated as

$$r = \frac{F - W}{U \cdot I} \tag{3}$$

where F, W, U, and I are the lifting force, the weight, the voltage, and the current, respectively.

Its mean value is

$$\bar{r} = \frac{\bar{F} - W}{\bar{U} \cdot \bar{I}} \tag{4}$$

The standard deviation of the weight/power ratio can be calculated as

$$\sigma_r = \sqrt{\left(\frac{\partial r}{\partial U} \cdot \sigma_U\right)^2 + \left(\frac{\partial r}{\partial I} \cdot \sigma_I\right)^2 + \left(\frac{\partial r}{\partial F} \cdot \sigma_F\right)^2} = \sqrt{\left(-\frac{\bar{r}}{\bar{U}} \cdot \sigma_U\right)^2 + \left(-\frac{\bar{r}}{\bar{I}} \cdot \sigma_I\right)^2 + \left(-\frac{\bar{r}}{\bar{F} - W} \cdot \sigma_F\right)^2} \tag{5}$$

Finally, the weight/power ratio for a success probability p is calculated as

$$\bar{r} - n(p) \cdot \sigma_r \tag{6}$$

where $n(p)$ is the number of standard deviations that corresponds to the probability p (under the hypothesis of normal distribution).

Results

Among the different tests, the current, the voltage and the lift ranged between 2.1 and 41 A, 8.8 and 16.7 V, and −1.9 and 31.2 N, respectively.

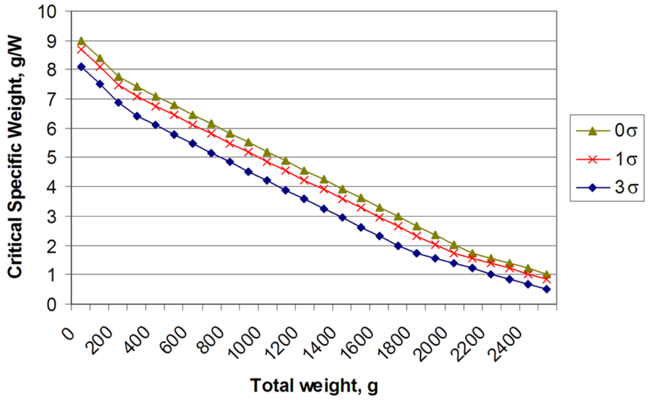

Fig. 1 Required specific weight for the helicopter energy-generation system versus total helicopter weight for different success probabilities.

The results obtained are displayed in Fig. 1. Each function represents the specific weights for different helicopter weights for a different success probability.

The ratio is linear, with different slopes in different zones: each zone corresponds to the same test, and available weight decreases linearly as used weight increases. There are different slopes because different tests are optimal over different ranges of the total weight. For high total weights, the best tests are those that give high lifting forces (30.2 N and 560 W were measured on the best test for high total weights). For lower total weights, some tests that have lower power consumptions are better (14.3 N and 162 W was the best test for low total weights).

For each weight, the critical ratio is the highest ratio of all the tests. Therefore, the resulting weight/power ratio functions are the upper enveloping curves of all the straight lines of every test of every series (Fig. 2).

Lower fuel-cell weight/power ratios are more difficult to achieve. But they are safer: they have a higher probability of lifting the helicopter successfully. The probabilities of success are 50% for 0σ, 84.13% for 1σ, and 99.87% for 3σ, assuming a normal probability distribution function for this specific weight. Therefore, the function obtained by subtracting 3σ from the specific-weight mean value is considered to be safe enough for noncritical operation, in which no human life or safety depends on the success.

The statistical uncertainty does not invalidate the results, but it is quite noticeable: for 3σ it gives a 1 g/W change on the 5 g/W weight/power ratio needed for an 1100-g load (the weight of the helicopter). This effect would be greater if a higher probability of success is needed. The uncertainty effect is higher in relative terms for higher loads.

Normal distribution is a good approach when many small effects are involved, such as in the critical ratio (measurements, atmospheric conditions, weights, etc.). Therefore, it is reasonable to assume a normal probability distribution for the weight/power ratio.

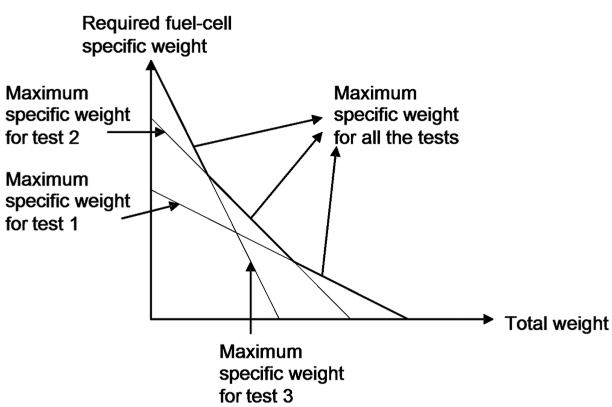

Fig. 2 Global specific weight as the upper enveloping curve of all the tests.

Table 1 Current values and predicted future values for the specific weight of fuel cells

		Specific weight, g/W
CSIC	Present	10
	Future	1.5[a]
NASA	Present	2.3
	Future	1.3

[a]Patent pending.

Discussion

New fuel-cell technologies allow a reduction in the specific weight of polymer electrolyte membrane fuel cells (PEMFC). This is possible because more than 90% of a common PEM stack is made up of nonactive material or components, used for feeding, sealing, or supporting the lightweight active membrane-electrode assembly. Heavy steel terminal plates, graphite bipolar plates, a gas connector, and pipes must be redesigned to minimize the global weight.

The following specific weights of fuel cells were obtained with PEMFC in the CSIC–IAI (Spanish Council for Scientific Research–Industrial Automation Institute, Spain) [10] and NASA (USA) laboratories, as shown in Table 1.

The present specific weight of fuel cells at CSIC–IAI has a failure probability of almost 100% in lifting just the helicopter weight. By contrast, all the other CSIC and NASA specific weights have success probabilities higher than 99.87% up to extra weights higher than 500 g (Fig. 1). The predicted specific weights for CSIC and NASA would have failure probabilities lower than 0.13% up to payloads higher than 900 g. As the weight/power ratio of fuel cells decreases, a higher payload can be carried with the same failure probability or the failure probability is lower for the same extra weight.

The amount of power needed in a helicopter of this size (some hundreds of watts) would make fuel-cell refrigeration important. The air movement caused by the blades could be used for this refrigeration. The voltage and the current needed by this helicopter point to a 20-to-40-cell PEM stack, with 20 to 100 cm^2 on each cell, as a possible option to power the helicopter.

Conclusions

Specific weight is critical for fuel-cell-powered helicopters: if it is higher than a critical amount, the helicopter is unable to fly.

Currently achievable fuel-cell specific weights (for costs lower than 10, 000 U.S./kW) are close to the calculated helicopter critical ratio. Therefore, improvements in specific weight would be useful (fuel cells for helicopters need lighter components). These improvements could be achieved by replacing the nonactive materials with lighter ones and/or others that require less thickness.

Lower fuel-cell specific weights are needed to lift heavy payloads or to meet strict safety requirements.

If the expected improvements turn out to be true, a fuel-cell-powered helicopter will be possible in the near future.

The relative uncertainty of the required specific weight is quite high. The width of the 99.74% central probability interval is 40% its average value for the helicopter weight and is higher for greater weights. Therefore, more experiments have to be done, especially because affordable fuel-cell specific weights are near to the critical one. For example, tests with more measures, to reduce the statistical uncertainty, or tests with apparatus that calculate the average values over long periods of time.

Acknowledgments

The current work has been supported by Research Projects: Autonomous Navigation of an Agricultural Robot (NARA) MCYT-DPI2004-07417-C04-03 and Design and Construction of a New Low Cost/High Efficiency PEM Fuel Cell (EPICO) MCYT-

ENE2005-09124-C04-02/ALT. The authors acknowledge Eugenio Villanueva for designing and constructing the lever system and the scales platforms, Javier Peral for aiding with the first helicopter platform, and José Javier Anaya and David Martin for sharing MATLAB functions.

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