Indoor Ionic Propulsion Technology – High Voltage Power System Design

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Abstract **- We present in this paper a novel propulsion technology that can directly convert high voltage electrical energy to mechanical thrust without using any moving mechanical parts and thus is noiseless and vibration free. In our prior work reported in late 2007, we demonstrated several prototypes using this technology and showed that simple triangular and circular propulsive units --Ionic Flyers -- could be lifted into air using off-the-shelf high voltage power system. However, the existing high voltage generators that can operate Ionic Flyers are usually large and heavy, which is not suitable for developing an autonomous ionic-propulsion flying system Therefore, we have since then developed a small-size and lightweight power generation system that is powered by an 11.1V battery but capable of generating ~20kV DC voltage continuously over time for a load in the MΩ range. The architecture and the performance analysis of this high voltage power system will be presented in this paper. In addition, the feasibility on lifting an Ionic Flyer with self-sufficient on-board power supply will be analyzed systematically based on the parametric models formulated by our group of the Ionic Flyer.**

Index Terms - Ionic Flyer, Ionic Propulsion, HV Power System

I. INTRODUCTION

Conventional aerodynamic principles have already been widely used in lifting and propelling flying systems such as helicopters and planes for many decades. These flying systems have been embedded with sensing and control systems for indoor and outdoor surveillance missions. However, powerful rotating/moving mechanical parts are usually used in order to generate strong aerodynamic flow for lift and propulsion. Therefore, these flying systems generate significant noise and strong mechanical vibrations during operation. As a result, the stability and thus the ability for capturing real time video information, in addition to surveillance performance, have greatly been degraded.

To address the above intrinsic problems, our group is currently exploring a novel indoor propulsion technology – ionic propulsion -- which generates propulsive force with no moving parts and noise. Thus far, we have demonstrated a new kind of propulsive element which we called "Ionic Flyer" (a common term used by enthusiasts who have also worked on this technology in a much less systematic manner). This ionic propulsive system converts high voltage electrical energy (usually higher than 10kV) directly to mechanical energy (ionic wind) for propulsion, and therefore, it does not contain any dangerous rotating/moving components which generate unwanted noise and vibration [1]. However, high voltage generators (kV range) are usually large and heavy which limits the possibility to make the Ionic Flyer to be applicable for autonomous flying systems. Therefore, the critical issues to be solved for this ionic propulsion technology are the miniaturization, weight reduction, and increased efficiency of a kV-range of high voltage (HV) power supply which is capable of generating high voltage (~20kV DC) continuously over time for operating Ionic Flyers. In this paper, we will first present the detailed parametric models and an optimal design methodology of the Ionic Flyer. Then, the architecture and performance of the prototype HV power supply system will be discussed. Finally, a feasibility analysis on self-sufficient on-board power supply for Ionic Flyers is presented.

II. BASIC INFORMATION OF THE IONIC FLYER

The Ionic Flyer is basically an asymmetrical capacitor which uses high voltage (usually higher than 10kV) to operate, and converts electrical energy directly to mechanical energy for propulsion. Therefore, it does not generate any undesired noise and vibration. Fig. 1 shows the basic structure of the Ionic Flyer with wire-plate electrode configuration (other configurations were discussed in [1]). The parameters L, h, d, and r_w represent the perimeter length, the collector height, the separation distance between electrodes and the radius of the emitter wire respectively.

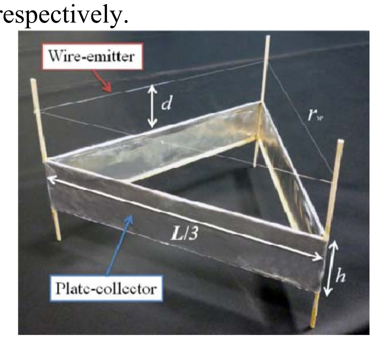

Fig. 1. Basic structure of a triangular Ionic Flyer with wire-plate electrode configuration.

The Ionic Flyer contains two primary elements – an emitter and a collector. The emitter is usually a thin wire which is connected to high voltage source, whereas the collector is typically a plate foil which is connected to ground.

By applying a high voltage between the two asymmetric electrodes, electric corona discharge will occur [2]. A high electric field near the wire-emitter causes the surrounding air molecules to become ionized which partially breaks down to produce a high density of ions. As a result, the charged ions are drifted towards the grounded plate-collector and this causes an electric current flow between the electrodes. During the movement of ions, high frequency collisions with neutral air molecules occurred. Momentum is transferred from the ionized gas to the neutral air molecules, resulting in movement of gas towards the collector. Therefore, thrust is generated by the Ionic Flyer from plate-collector to the wire-emitter. If the input power is high enough, the output force will balance its own-weight and therefore the Ionic Flyer can be lifted up.

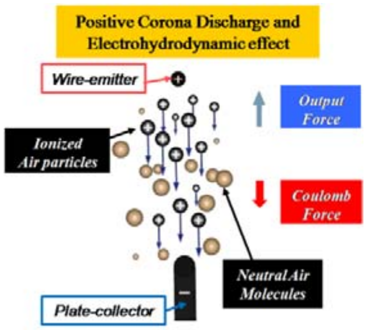

Fig. 2. Illustration showing the basic operating principle of ion-generation between two asymmetric electrodes [1].

III. Parametric Models Of The Ionic Flyer

Based on the lifting phenomenon of the Ionic Flyer, Chung and Li performed systematic experimental analyses on Ionic Flyers with wire-plate electrode configuration and introduced parametric models which are critical to the understanding of the operational principles of the Ionic Flyers [1]. Moreover, the effects of all primitive parameters that affect the performance of the Ionic Flyers have also been determined. The Current-Voltage model for Ionic Flyers with wire-plate configuration is given as

$$I = C(L,d)(V - V_0(r_w, d))^2 \qquad (1)$$

where I is the input current in mA, V is the input voltage in kV, C is the current gain which is written as

$$C(L,d) = K_e \cdot L/d^2 \qquad (2)$$

where K_e is the environmental constant in mA/mm·kV^2 which reflects the changes of the environmental conditions. V_0 is the onset voltage which is described as

$$V_0(r_w, d) = G(r_w) m_0 g_0 \delta \left(1 + \frac{0.0301}{\sqrt{\delta \cdot r_w}}\right) r_w \cdot \ln\left(\frac{d}{r_w}\right) \qquad (3)$$

where m_0 is irregularity of the wire, δ is the air density factor, g_0 is the breakdown field strength, and G is the derived modification factor given as:

$$G(r_w) = 1 + e^{-\left(\frac{r_w}{4\times10^{-5}}\right)}. \qquad (4)$$

According to (1), it is shown that the current and voltage are related quadrically. While the force and voltage are related linearly by:

$$F = J(L,d)(V - V_f(V_0)) \qquad (5)$$

where F is the generated force in gram, V is the input voltage in kV, J is the force gain which is written as

$$J(L,d) = K_f \cdot L/d^{0.54} \qquad (6)$$

where K_f is the lift-force environmental constant with units of g/mm$^{0.46}$·kV^2, which depends on the environmental conditions. V_f is the barrier voltage which represents the minimum input voltage for the Ionic Flyer to create force. It is related to the maximum power loss before the Ionic Flyers is able to generate lift-force and this power loss P_c is called Initial Power Dissipation (IPD). It is found to be proportional to the perimeter length L of the Ionic Flyer and defined as

$$P_c = K_p \cdot L \qquad (7)$$

where K_p is the IPD constant which represents the maximum power loss per unit length in the process of corona discharge. By substituting V_f into (1) and P = IV, the IPD can also be derived and V_f can be determined by

$$P_c = CV_f(V_f - V_0)^2 = K_p \cdot L \qquad (8)$$

Finally, using the above equations, a third-order equation for the Lift-force to Power Relationship is described by

$$P = C\left(J^{-1}F + V_f(V_0)\right)\left(J^{-1}F + V_f(V_0) - V_0\right)^2 \qquad (9)$$

where P is the input power in Watt, F is the output force in gram, and J^{-1} is the reciprocal of the force gain J (refers to (6)).

Using these parametric models, the structural design of the Ionic Flyer can be optimized by finding the maximum Force-to-Power ratio which is derived from (1) and (5) as

$$\frac{F}{P} = K_{f/e} d^{1.46} \frac{(V - V_f(V_0))}{V(V - V_0)^2} \qquad (10)$$

where $K_{f/e}$ is an environmental constant, equal to K_f / K_e.

As indicated by (10), the F/P ratio only depends on the applied voltage V and gap distance d. Therefore, Ionic Flyers with optimal force/power ratio can be obtained based on engineering requirements. Fig. 3 shows the parametric plot of (10) using empirical data collected by Chung and Li [1]. The Ionic Flyers used in this paper were built using this design data.

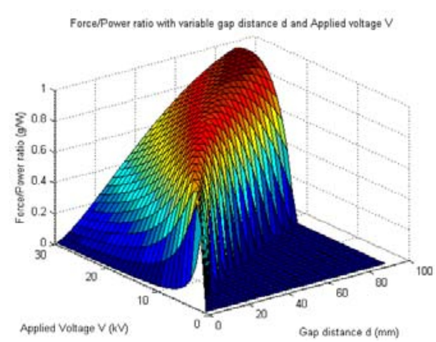

Fig. 3. Variation of Force-to-Power ratio with gap distance and applied voltage. (K_e = 0.001755mA/mm·kV^2, K_f = 0.005238 g/mm$^{0.46}$·kV^2).

IV. Design of High Voltage Power System

In order to use the Ionic Flyer for autonomous flying systems, a small-sized and lightweight High Voltage power supply is currently under development in our laboratory. The power supply should be capable of supplying high DC voltage of ~20kV under a wide range of load in MΩ range from a light weight battery, in order to drive the Ionic Flyer effectively. To achieve this, selection of different components of the HV power system are discussed in the following sections. Also, some prototypes of the control circuit are described in order to show the important issues encountered during the development process.

Fig. 4 and Fig. 5 show the basic configuration of the power supply which is composed of 1) Battery, 2) Step-up Transformer, 3) Voltage Multiplier, and 4) Control Circuit.

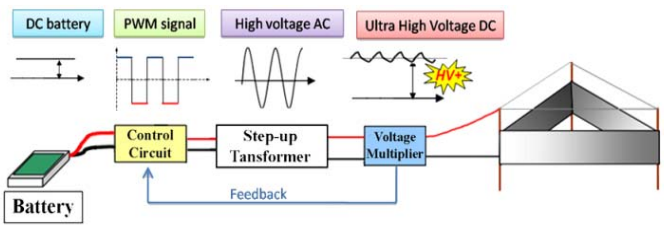

Fig. 4. Basic configuration of the High Voltage Power Supply.

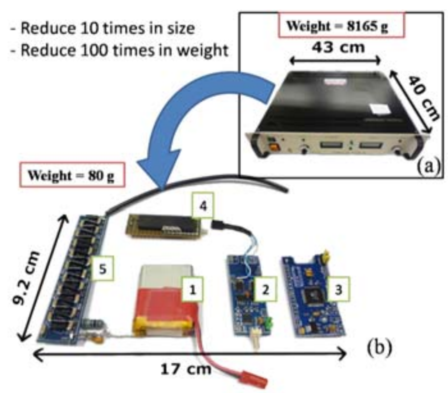

Fig. 5: (a) A conventional HV Power Supply which is usually used to operate Ionic Flyers; (b) new battery-driven HV Power-Supply developed by our group (1: Battery, 2: Control Circuit, 3: Microprocessor + Bluetooth, 4: Piezo Transformer, 5:Voltage Multiplier).

A. Battery

A single battery is used as the power source for the entire HV power supply, and therefore it should have a high energy density. Table I shows the comparison of the six most commonly used rechargeable battery [3]. From the table, it is clear that Lithium-ion Polymer (Li-Poly) battery has the best Weight-to-Energy ratio among the other batteries and the weight of battery can be calculated by

$$W_b = R_b \times P \times t \tag{11}$$

where R_b is weight-to-energy ratio of the battery in g/W·h (≈ 6.1 g/W·h for Li-Polymer), P is the output power in Watt, and t is the operation time required in hour. We used a 3-cell Li-Poly battery in the design which gives around 11.1V to the HV power system.

TABLE I
CHARACTERISTICS OF MOST COMMON RECHARGEABLE BATTERY

Battery	Gravimetric Energy Density (Wh/kg)	Weight-to-Energy ratio[a] (g/W·h)
NiCd	45-80	16
NiMH	60-120	11.1
Lead Acid	30-50	25
Li-ion	110-160	7.4
Li-ion polymer	130-200	6.1
Reusable Alkaline	80 (initial)	12.5

[a]Weight-to-Energy ratio represents the weight in gram per unit Watt-hour, i.e., when the ratio is smaller, the energy density is higher.

B. Step-up Transformer

The step-up transformer can generate high voltage AC output from a relatively low voltage. Conventionally, high frequency coil transformer is used; however, those electro-magnetic transformers will generate high electro-magnetic interference (EMI) which affects the wireless control and sensing systems. In addition, the main disadvantage of the coil transformer is the heavy weight which diverges from the objective of miniaturizing both the weight and volume of the power system, i.e., the weight-to-power ratio of coil transformer is high compared to the piezoelectric ceramic transformer that is used in our HV power system [4].

Piezoelectric ceramic (PZT) transformer generates high voltage efficiently without any magnetic material, so it will only induce a very low EMI which does not affect the other components in the system. On the other hand, it is non-flammable and has an excellent weight-to-power ratio, usually less than 1 g/W. The weight of the transformer can be found by

$$W_t = R_t \times P \tag{12}$$

where R_t is weight-to-power ratio of the transformer in g/W (≈ 0.864 g/W for our design), and P is output power required in Watt.

C. Voltage Multiplier

The output voltage of transformer is further amplified and rectified by the Cockcroft Walton (CW) voltage multiplier in order to drive the Ionic Flyer. The CW circuit is made up of a voltage multiplier ladder network of capacitors and diodes to generate high voltage. Using only capacitors and diodes, it can step up a relatively low voltage to extremely high value, while at the same time being far lighter and cheaper than transformer. Besides, the voltage across each stage of the cascade is equal to twice of the peak input voltage, so feedback can be drawn from the first stage with potential divided in order to sense the output voltage of the power supply.

Usually, the capacitance of the HV capacitors in a CW circuit is not the issue of concern when designing a HV power supply, i.e., the performance of the circuit does not depend on the capacitance [5]. However, it does affect the output when the capacitance is low and the current output is relatively large. Fig. 6 shows the performance of the CW circuit used in our system with different capacitance for I_{out} = 0.5mA. It shows that the capacitance should be large enough in order to provide sufficiently high voltage to drive the Ionic Flyers Hence, in our design, a silicone-sealed 10-stage CW circuit with 1000pF SMD HV capacitors is used for the HV power supply.

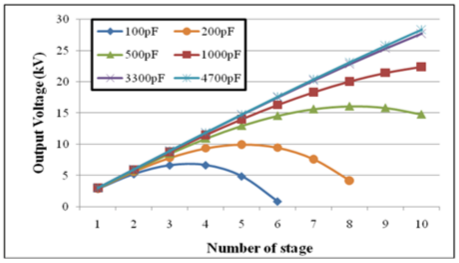

Fig. 6. Output of CW circuit using different capacitances (I_{out} = 0.5mA, V_{in} peak = 1.5kV, and frequency = 47kHz).

D. Control Circuit

The main objective of the control circuit is to convert DC voltage into pulsed DC voltage under specified frequency in order to drive the PZT for voltage step-up. By sending the driving signal, the input voltage is switched with specified frequency and acts as the input of the PZT. However, there will be short-circuit and large shoot-through currents, caused by P-MOS and N-MOS circuit, remaining simultaneously during transitions. Therefore, this should be prevented by implementing small time delays between the driving signals. These delays allow the N-MOS to turn off before the P-MOS turns on and vice versa.

There are two kinds of switching algorithm – Half H-bridge and Full H-Bridge. Fig. 7 shows the differences and the outputs between the two algorithms. The Half H-Bridge algorithm can generate a unipolar pulsed DC which is from 0V to +11.1V, whereas the Full H-Bridge can give a bipolar pulsed DC that is from -11.1V to +11.1V. These two algorithms developed and tested in our prototype systems.

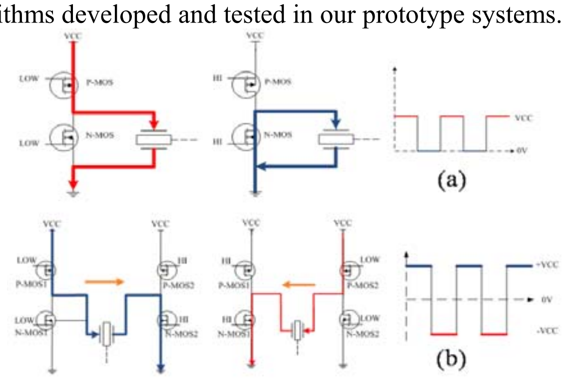

Fig. 7. (a) Half H-bridge switching algorithm. (b) Full H-bridge switching algorithm

On the other hand, the control circuit also acts as a user control interface. It allows users to control the system wirelessly using Bluetooth technology. Users would be able to get system information, activate the system, and control the driving signal in order to control the output of the power supply.

E. Experimental Prototypes

1) First Prototype

The first prototype used the Half H-bridge switching algorithm in order to pulse the DC voltage from battery and drive the PZT. The output of the power system of this system is 13.54kV DC at 0.17mA under 80MΩ load, when the input is 11.1V at 0.60A. The efficiency is about 35%. When this high voltage DC output is connected to the Ionic Flyer, a lift force was generated, but was not enough to balance the weight of the Ionic Flyer, i.e., the Flyer could not be lifted off the surface of a table. By increasing the input voltage from 11.1V to 14.8V, the output of the power supply increased to 18.06kV DC (at 0.20mA), and the Ionic Flyer could be lifted a little bit.

Although this first prototype could balance the weight of Ionic Flyer, it required a 14.8V battery (i.e. 4-cell Li-Poly battery) as the input power source. Also, the Ionic Flyer was just lifted a little bit off a table's surface. Therefore, we have concluded that the Half H-Bridge produces insufficient power to operate the Ionic Flyer.

2) Second Prototype

As the first prototype cannot lift the Ionic Flyer effectively, the Full H-bridge switching algorithm was used in the second prototype. Full H-bridge needs two inverting pulsed DC voltages in order to drive the PZT correspondingly. As a higher current is needed to drive the Full H-bridge circuit, inverting the driving signals was performed at the TTL state (i.e., the signal from signal generator). Thus, two inverting pulsed DC voltages with small delay times are generated using H-bridge and input them to the PZT. The output of this power system is 19.60kV DC at 0.35mA under 80MΩ load, when the input is 11.1V at 1.58A. The efficiency is about 39%. When connecting the high voltage DC to the Ionic Flyer, a lift force was generated by Ionic Flyer which could lift itself stably without any noise.

We caution here that although the system described above could lift an Ionic Flyer, electrical ground loop could easily occur for the system circuit, due to high voltage output, high current drawn and high frequency switching. This could cause unstable power source to the system circuit, and thus the electronic components will not perform well, especially the microprocessor which gives driving signal to the control circuit. Besides, because of the high voltage output and high frequency switching, the wireless Bluetooth transmission tasks would be difficult to perform.

3) Third Prototype

To solve the problem of the second prototype, two isolated grounds were built in order to separate low power components (such as microprocessor and Bluetooth chip) and high power components (i.e., MOSFET pairs, PZT, and CW circuit). This isolation can reduce the interference between them and allows the entire system to function more stably and effectively.

Since to reduce overall power system weight, a single battery is used for the whole system, and hence an isolated

DC-DC converter is needed for two isolated-ground circuits. Digital isolators are used for the logic signal transmission between two isolated-ground circuits, i.e., enabling signal and driving signal of the PZT. While for analog signal transmission, i.e., feedback voltage, an isolation amplifier will be used in order to give a linear feedback signal from CW circuit to the microprocessor.

Using this configuration, we have demonstrated that the power supply could operate stably and the users could control the system using wireless Bluetooth communication effectively.

TABLE II
COMPARISON BETWEEN THE PROTOTYPES

	First Prototype	Second Prototype	Third Prototype
Switching Algorithm	Half H-Bridge	Full H-Bridge	Full H-Bridge
Input [a]	11.1V@ 0.60A	11.1V @ 1.58A	11.1V @ 0.03-1.85A
Output [a]	13.54kV @ 0.17mA	19.60kV @ 0.35mA	0-25.2kV @ 0-0.27mA
Efficiency	35%	39%	~35%
Operation of Ionic Flyer	Not enough force generated to lift the Ionic Flyer.	Enough force to list the Ionic Flyer stably without any noise. But, cannot be controlled through Bluethooth due to electric ground loop problem.	Ionic Flyer can be lifted and the force can be controlled using Bluetooth communication.

[a] Input and output of the prototypes were measured under 80MΩ load.

F. *Resonant Frequency Tracking Algorithm*

The PZT is required to be driven under the resonance frequency in order to get the highest step-up voltage gain, but the resonance frequency will be shifted during operation due to temperature and environmental variations. Therefore, a resonance frequency tracking system which compares the feedbacks from the voltage multiplier was built into the control circuit.

Initially, the driving frequency is set near the resonance frequency of the PZT. Once the controller enables the system, a high voltage is generated, a feedback signal (Feedback0) is received from the multiplier. After that, the controller will start changing the driving frequency in one direction (increase or decrease) and hence another feedback signal (Feedback1) is received. By comparing magnitude of Feedback0 and Feedback1, the variation of output voltage due to the change of driving frequency is known.

The controller keeps the change of the driving frequency when the output is increased, i.e. Feedback1 is greater than Feedback0. Similarly, the driving frequency is restored when the output is decreased, i.e., Feedback1 is smaller or equal to Feedback0, and the driving frequency is changed in opposite direction (increase or decrease) in the next iteration.

Using this algorithm, the driving frequency that gives maximum output, i.e., resonance frequency, can be reached in a short period of time. Also, it is tracked during operation in order to achieve the highest performance.

V. PERFORMANCE OF HIGH VOLTAGE POWER SUPPLY

A. *Variation with Frequency*

As described in the last section, the power supply generates high voltage using a PZT, hence its output voltage varies with the driving frequency. After a parametric experimental study, the PZT is shown to perform the best when resonance frequency (about 46 kHz) is reached.

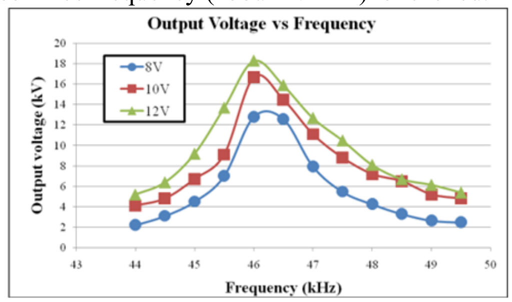

Fig. 8. Dependence of the high voltage output on the driving frequency.

B. *Varying the Duty Cycle*

The output voltage will also vary with the duty cycle of the driving signal. Experimental analysis shows that the highest output voltage is achieved when duty cycle is 40%. Note that by tuning the duty cycle, the output voltage can be controlled. As the force generated by Ionic Flyer depends on the applied voltage, the force can also be controlled by tuning the duty cycle of driving signal.

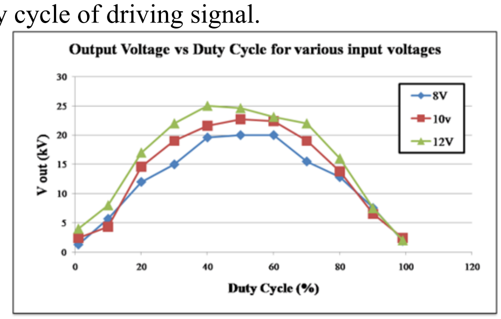

Fig. 9. Output voltage vs duty cycle of the driving signal for various input voltages.

C. *Efficiency*

During the step-up process, power is lost due to heat dissipation, corona discharge, and other environmental issues. The efficiency of the power supply can be found by plotting the power input versus output as shown in Fig. 10. For our HV power supply, the efficiency is about 36 %.

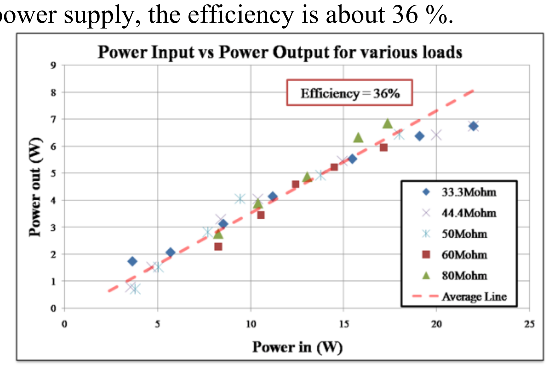

Fig. 10. Power input vs power output for various loads.

V. SELF-SUFFICIENT ON-BOARD POWER SUPPLY ?

Some researchers and hobbyists who built and studied the Ionic Flyer technology would like to achieve the goal of lifting an Ionic Flyer with self-sufficient on-board power supply (e.g., [6][7]), but to the best of our knowledge, no one have been successful so far. The possibility of developing a self-sufficient on-board power supply may be analyzed systematically using the parametric models which were described in Section II.

Assume W is the total weight of the HV power supply, the total net force F_{net} is

$$F_{net} = F - W \tag{13}$$

If F_{net} is greater than zero, it means that there is a net force to lift the Ionic Flyer. In other words, the Ionic Flyer can be lifted up along with the on-board power supply. This can also be proved by finding the Net-Force-to-Power ratio (F_{net} / P) to be greater than zero as the Power P is always a positive real number.

Without loss of generality, power loss is ignored and only the essential components of a portable power supply, i.e., the battery and the step-up transformer, are counted as the total weight of the power supply. Using (5), (11), (12) and (13), the Net-Force-to-Power ratio is derived as

$$\frac{F_{net}}{P} = \frac{J(V - V_f(V_0) - R_b \times P \times t - R_t \times P}{P} \tag{14}$$

By $P=IV$ and after simplification, (14) becomes

$$\frac{F_{net}}{P} = K_{f/e} d^{1.46} \frac{(V - V_f(V_0))}{V(V - V_0)^2} - R_b \times t - R_t \tag{15}$$

where $K_{f/e}$ is the environmental constant, equal to K_f / K_e (refer to Section II for details). From the equation, the Net-Force-to-Power ratio only depends on the gap distance d, applied voltage V and the operation time t. Assume the operation time is 5 minutes, the Net-Force-to-Power ratio with various gap distance d and applied voltage V can be calculated. Fig. 11 shows the minimum gap distance and applied voltage required in order to make the Net-Force-to-Power ratio greater than zero.

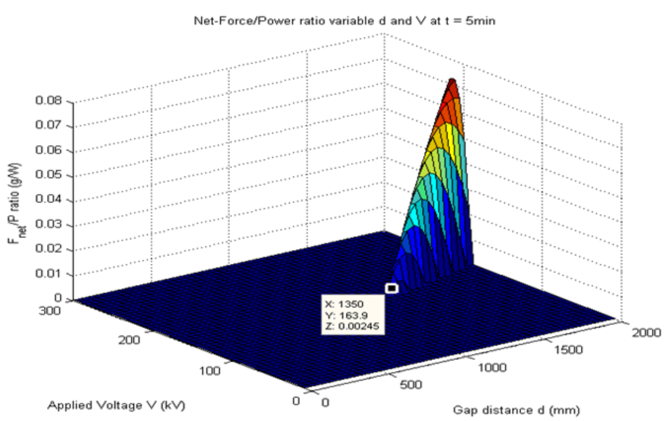

Fig. 11. Net-Force/Power ratio with variable gap distances and applied voltages for t = 5min (K_e = 0.001755mA/mm·kV^2, K_f = 0.005238 g/mm$^{0.46}$·kV^2, R_b=6.1 g/W·h, R_t=0.864 g/W).

So, to lift an Ionic Flyer with its own on-board power supply and stay in air continuously for 5 minutes, a gap distance = 1.35m between the wire and the vertical plate capacitors (Fig. 1) and an applied voltage =163.9 kV are required. Such a high voltage output is impossible to generate from a miniaturized HV power supply using the state-of-the-art technology (to the best of our knowledge after extensive Internet search). Besides, the Net-Force-to-Power ratio achieved in the above configuration is only 0.00245 g/W when ignoring the actual weight and power loss. Hence to the best of our knowledge and based on the parametric equations, it seems that it is impossible for the Ionic Flyer to be lifted up with an on-broad power supply (i.e., battery, transformer and circuits) using only the force generated by the Ionic Flyer, giving the state-of-the-art voltage conversion and power storage technologies.

For this reason, an auxiliary lifting system, e.g., a helium blimp, is proposed for balancing the payload of the whole system. That is, the whole system can float in air and be propelled through air using the propulsive force generated by Ionic Flyer.

VI. CONCLUSION

This paper presents a design methodology for optimizing the force generated by the Ionic Flyer – a novel thrust generation system that uses high voltage to give thrust without any noise and moving mechanical parts. An extensive analysis was performed to understand the power-input to lift-force efficiency of the Ionic Flyer — which showed that it is not feasible to lift an individual Ionic Flyer with its own on-broad power supply, given the state-of-the-art power generation technology. However, a lightweight, battery-driven, and miniaturized high voltage supply was developed in order to allow the Ionic Flyer to be attachable and provide thrust to flying systems, e.g., a blimp. The development of an *Ionic Propulsion Blimp*, which uses the blimp as the auxiliary lifting system and Ionic Flyer as the thruster, is underway in our group and will be reported at IEEE ICRA 2009.

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