A Study on Flywheel Energy Recovery from Aircraft Brakes

Michael A. Conteh and Emmanuel C. Nsofor
Department of Mechanical Engineering & Energy Processes,
Southern Illinois University,
Carbondale, IL 62901, USA

***Abstract*—This study on the flywheel for harvesting energy from aircraft brakes is for converting the high landing kinetic energy of aircrafts to useful electrical energy. Energy recovered was established by determining the kinetic energy of the landing aircraft after the action of other decelerating mechanisms of the aircraft. This is the energy dissipated at the wheel brakes as heat. With the aid of the modified Bréguet equation and other useful parameters, the energy of this flywheel was determined. Further analysis and application led to possible electrical energy that can be stored in batteries located on the ground. Results show that more than half of the dissipated energy at the wheel brakes can be converted to electricity. Consequent additional weight to the aircraft due to this system was found to be less than 0.5% of the aircraft's maximum take-off weight. This can be offset by choice of materials and slightly reducing the design pay load to ensure that the structural efficiency of the aircraft is maintained. Applying this system with a conservative estimate of 5 landings per day for the Boeing 777 aircraft family in active service today shows total energy savings comparable to a medium coal-fired power plant electricity supply.**

I. INTRODUCTION

Energy management has been found to be one of the most promising cost-reduction and profit promising improvement programs for solving the energy availability problem. Energy conservation that was once considered insignificant for energy resource development is now one of the most important approaches for meeting the demand. Storage technologies are becoming practical solutions for situations where energy is required to be saved. Today, viable energy storage technologies include flywheels, batteries and ultracapacitors. Due to new improvements in materials and technology, the flywheel has recently re-emerged as a promising application for energy storage [1-3]. When compared to conventional energy storage systems based on battery storage technology, flywheel energy storage has many advantages which include (a) high power/energy density (b) much less environmental problems, (c) availability of output energy directly in the mechanical form and (d) high efficiency.

The flywheel offers several unique advantages as an energy storage device [4-6]. Paramount among them is its high power and energy density. This significantly reduces the weight and volume of an energy storage system. Its ability to store substantial energy for the least weight is one of the advantages of this application. A number of reports [1, 7-11] have shown that the energy density a flywheel can achieve depends on the density of the material and the geometric shape. In this regard many studies such as [1-2, 4-5, 12-13] have shown that composite materials are suited for flywheel applications due to their large specific strength.

In the study presented here, fundamental investigations were performed on harvesting energy from aircraft brakes. A viable application of high-speed flywheel energy storage system for this energy harvesting was developed. Analytical and computational studies on harvesting of the energy from the brakes were performed leading to results for an advanced composite material for high-speed, high-energy density flywheel for energy harvesting/storage from aircraft brakes. The flywheel is aimed at converting the high landing kinetic energy of aircrafts to useful electrical energy while minimizing temperature and wear of the brakes. Results from the study show that for a typical aircraft, more than half of the dissipated energy at the wheel brakes can be harvested and converted to electricity. Consequent additional weight to the aircraft due to this system was found to be less than 0.5% of the maximum takeoff weight.

II. LANDING KINETIC ENERGY OF AIRCRAFTS

Bringing a landing aircraft to rest requires dissipation of its *KE* which is done through the braking system. This consists mainly of the thrust reversers, spoilers and wheel brakes. The *KE* that is not absorbed by other parts of the braking system is absorbed by the wheel brakes. The *KE* of the aircraft at touchdown is given by the expression

$$\boldsymbol{KE} = \frac{1}{2}\left[\boldsymbol{M_1} - \boldsymbol{M_f}\right]\boldsymbol{v}^2 \quad (1)$$

where M_1 is mass of the aircraft at takeoff and M_f is the mass of fuel burnt during the mission and v is the velocity of the aircraft at touchdown. Thus the landing *KE* of an aircraft depends on the takeoff weight and the flight distance.

The constant angle of attack – constant velocity cruise range incorporated in the Bréguet Range equation was originally used by Devillers and Coffin

[14]. It is a compact way for calculating the gross still air range, i.e., the cruise distance until all the fuel is used up. The equation is given as:

$$\boldsymbol{R = \frac{1}{c}\frac{VL}{D} ln\left(\frac{W_1}{W_2}\right)} \quad (2)$$

where c is the thrust specific fuel consumption, V is the cruise velocity, L/D is the lift to drag ratio and W_1 and W_2 are the takeoff and touchdown weights of the aircraft respectively. Randle et al. [15] used the Bréguet range equation and flight data to develop a model that could be applied to any given flight and aircraft type to predict the fuel burnt during a mission. This model can be expressed as

$$W_f = W_1\left(1 - exp\left\{\frac{-S_{gr}}{H_{cr}(1-V_{HW}/[M_{cr}\sqrt{\gamma R T_{cr}}])}\right\} + \frac{\Delta W_{lost}}{W_1} - \frac{\Delta W_{rec}}{W_1}\right) \quad (3)$$

where W_1 is the take-off weight, S_{gr} is the ground-track distance between two airfields, H_{cr} is the range factor, V_{HW} is the head wind velocity, M_{cr} is the cruise Mach number, T_{cr} is the temperature at the cruise altitude, γ and R are the ratios of specific heats and gas constant of air respectively, ΔW_{lost} is the fuel lost during the climbing and ΔW_{rec} is the fuel recovered during the descent and landing segment of the flight. The range factor is the parameter H_{cr} that gives the aerodynamic and propulsive efficiency of the aircraft. This study determined the range factor from flight data and validated it with mean values obtained from aircraft payload-range diagrams [16].

III. DESIGN AND ANALYSIS OF THE COMPOSITE FLYWHEEL ENERGY RECOVERY SYSTEM

Fig. 1 shows the schematic diagram of the energy recovery system consisting of the wheel and brake unit, the clutch, the transmission mechanism, the flywheel, the charging unit and a set of batteries. The transmission is to give the flywheel an opposite rotational motion to the landing gear wheel. Thus, the aircraft will slow down such that the applied brake pressure would be a minimum. The motion of the flywheel will rotate the alternator to produce the necessary current to charge the batteries, which are located on the ground at the gate to prevent additional weight on the aircraft. In general, flywheel systems have energy losses due mainly to bearing friction, which makes them less efficient than a battery-based system for storing energy for long periods of time. The combined arrangement of the flywheel and battery system is to make use of the advantages of each method.

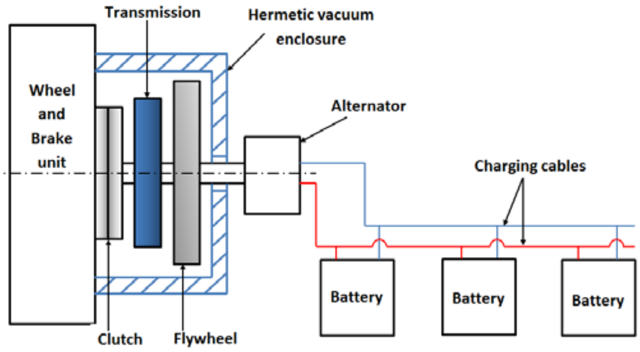

Fig. 1: Flywheel energy recovery and storage system

A. Energy recovered

Parameters for Boeing 777-300ER aircraft in standard flight between St. Louis, MO, US located at 83°44 '55" N, 90° 22'12" W and Los Angeles, CA, US located at 33°56'33" N, 118°24'29" W were used in design and testing the analysis. Great Circle Mapper was used to obtain the distance between the two cities. Parameters for the aircraft and other data used are shown in Table 1.

The Bréguet range equation and flight data were used to obtain the mass of the fuel burnt during the flight. It is known that due to other deceleration mechanisms of the aircraft only about 25% of the landing kinetic energy (KE) is dissipated as heat at the wheel brakes. The possible amount of energy that can be harvested and stored in the batteries is given by:

$$Energy\ Stored = 0.25\eta_1\eta_2 KE \quad (4)$$

where η_1 is the flywheel energy harvesting efficiency and η_2 is the conversion efficiency.

Table 1: Parameters and Data used

	Parameter	Value
1	M_1 = MTOW	351,535 kg [17]
2	V_{HW}	38 km/h [15]
3	M_{cr}	0.84 [18]
4	γ	1.4
5	R	287 J/K-mol K
6	T_{cr} at 35,000 ft	218.16 K [19]
7	H_{cr}	30909 km [15]
8	$\Delta W_{lost}/W_1$	0.0152 [15]
9	$\Delta W_{rec}/W_1$	0.001 [15]

For the case described the energy available at the flywheels was obtained as 83 MJ while the energy to be stored in the batteries was obtained as 71 MJ. This is more than half of the energy wasted as heat at the wheel brakes. Boeing Aircraft Company data shows that the company have delivered 1,222 Boeing 777 aircrafts between 1995 and August 2014. With an 85% conservative estimate, there are about 1040 Boeing 777 in active service. Using the results from the analysis and a conservative average of 5 landings per day for each of them gives total energy savings per day equivalent to the capacity of a 4.5 MW power plant. For the purpose of obtaining the geometrical dimensions for the clutch and transmission for the system, it is noted that there are two main landing gears with each landing gear having 6 wheels in tandem pair. Thus, the energy available at each flywheel is about 6.92 MJ.

B. Clutch system

Fig. 1 shows that the clutch is attached to the wheel in such a way as to connect the wheel and transfer rotational movement to the flywheel through the transmission system during landing and taxiing. The flywheel is disconnected during taxiing out for takeoff.

The power, *P*, transmitted by the clutch, is given as,

$$\boldsymbol{P = T\omega} \tag{5}$$

where T is the torque and ω is the angular velocity.

The two theories on the torque for producing a slip between the surfaces of a clutch are (a) the uniform pressure and (b) the uniform wear theories. The uniform wear theory is usually preferred as it results in a lower calculated torque for a given axial force. For a flat plate clutch, using the uniform wear theory, the torque, T, is given as,

$$\boldsymbol{T = \frac{\mu W}{4}[D_o + D_i]} \tag{6}$$

where μ is the coefficient of dry friction between the surfaces of the clutch, *W* is the axial applied force, and D_o and D_i are respectively, the outside and inside diameters of the clutch. Using the diameters for the Boeing 777-300 ER landing gear wheel, the case for the clutch with D_o = 0.4 m, D_i = 0.3 m, μ = 0.3 and *W* = 500 N was considered. The torque for transmitting motion to the transmission system was found to be 26.25 Nm.

Since the clutch is attached to the wheel, its angular velocity will be that of the wheel. Thus, with a landing velocity of 115 knot (212.98 km/h = 59.169 m/s), the angular velocity of the clutch was found to be 89.65 rad/s (856.1 rev/min). Thus, the power transmitted by one face of the clutch at 856.1 rpm is about 2.353 kW.

C. Transmission system

Fig. 2 shows a single stage epicyclic gear. It consists of the planet, P, planet carrier, L, sun wheel, S and the annulus ring, A. Three possible configurations of the epicyclic gear train are ***star*** (planet carrier arm is fixed and the sun and annulus ring gears rotate), ***planetary*** (annulus ring gear is the fixed component and the sun gear and planet carrier arm rotate), and ***solar*** (sun gear is fixed and the annulus ring gear and planet carrier arm rotate).

Since the purpose of the transmission system is to give the flywheel an opposite rotational motion to the brake wheel, the star configuration was selected for this preliminary study. This is because, out of the three possible configurations, the star configuration is the only one that can give the output shaft an opposite rotational motion.

Assuming that N_1 and N_2 are the rotational speeds of the input and output shafts respectively, the velocity ratio velocity ratio, *G*, of the transmission system is given as,

$$\boldsymbol{G = \frac{N_2}{N_1}} \tag{7}$$

Since the input shaft of the transmission system is connected to the clutch, the angular velocity of the input shaft is 89.65 rad/s. The output shaft is connected to the flywheel, which according to the dimensions used has an angular velocity of 9507.81 rad/s. Thus, the output shaft's angular velocity is that of the flywheel. The velocity ratio of the proposed transmission system was calculated to be 106.

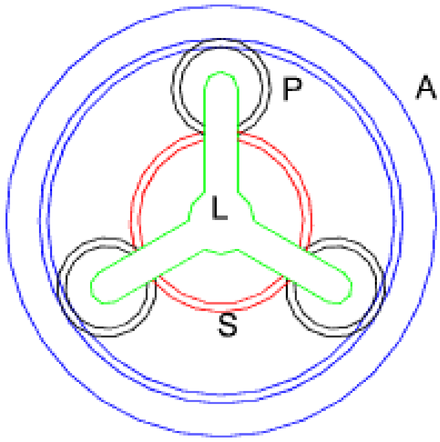

Fig. 2 Single Stage Epicyclic Gear Train

D. Additional weight to the aircraft

1. Flywheel:

Fig. 3 shows a section view of the proposed flywheel. It is a constant stress disk with a constant thickness rim. Results by Georgian [20] show that the center of the disk becomes prominent for large values of $\ln(h_o/h_a)$. Thus, the center cannot carry its share of the rim load. The study gives the limit of $\ln(h_o/h_a)$ for the flywheel dimensions. For appropriate dimensions of the flywheel, the value $\ln(h_o/h_a) = 1.2$ was used in this study to determine the profile of the disk.

The profile of the disk is given as,

$$\boldsymbol{h = h_o e^{-BX^2}} \tag{8}$$

and the mass, *m*, and mass moment of inertia of the flywheel can be shown to be,

$$\boldsymbol{m = \rho\pi h_a r_a^2 \left[\frac{e^{-B}(e^B - 1)}{B} + \left(\frac{r_b}{r_a}\right)^2 - 1\right]} \tag{9}$$

$$I = \rho\pi h_a r_a^4 \left\{\frac{(-B + e^B - 1)}{B^2} + \frac{1}{2}\left[\left(\frac{r_b}{r_a}\right)^4 - 1\right]\right\} \tag{10}$$

where $B = \frac{\rho\omega^2 r_a^2}{2\sigma}$ and $X = \frac{r}{r_a}$. h_o, h_a, r_a and r_b are as shown in Fig. 4, ρ the density of the material and ω the rotational speed of the flywheel and σ is the constant stress in the disk.

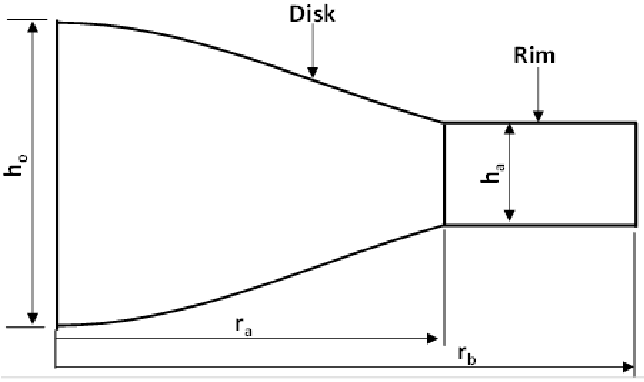

Figure 3: Proposed Flywheel

Using the flywheel dimensions and material properties, the mass of the flywheel was determined to be 10.33 kg.

2. Clutch

Using the dimensions of the clutch disks with a composite material density of 2000 kg/m^3 and thickness of each disk of 20 mm, the mass of the clutch can be shown to be 4.4 kg.

3. Transmission System

If high tensile steel is used to produce the planets, sun wheels, annular rings and planet carriers with a thickness of 20 mm for each of these components, the total mass of the transmission was found to be approximately 78 kg.

4. Enclosure

The material used for the analysis is aluminum alloy A206 with density of 2700 kg/m^3. With a 10 mm thick enclosure, the mass was found to be 48 kg.

Thus, the unit additional mass is 140.7 kg. Since there are 12 wheels, the total additional mass is 1,688.8 kg. This total additional mass is about 0.48% of the maximum take-off weight which can decrease depending on careful choice of materials for the different parts of the system. Also, the total additional mass can be balanced by reducing the design pay load while ensuring the structural efficiency of the aircraft is not altered.

IV. CONCLUSIONS

This study on energy recovery from aircraft brakes via the flywheel system shows that more than half of the energy dissipated at the wheel brakes as heat can be harvested and converted to electricity. It shows that the energy wasted in this way also comes along with other undesirable consequences. Instead of this, the study found that more than half of this energy can be recovered and made useful. This will also contribute to increasing the life of the wheel brakes. Further studies showed if this method is applied to all the active commercial Boeing 777 aircraft using a conservative estimate of 5 landings per day, total energy that is equivalent to the capacity of a 4 MW power plant will be saved. This is just for the Boeing 777 aircraft. To better appreciate this energy savings, it should be noted that data from the General aviation Manufacturers Association [21] estimates that in 2004, the number of aircraft worldwide excluding helicopters included 312,000 active general aviation aircraft, 18,000 passenger aircraft and 89,000 military aircraft.

The study also shows that the dimensions of the flywheel to be used to make this system possible are reasonable. The energy loses in the energy transmission were accounted for in the harvesting and conversion efficiency. Additional weight to the aircraft was determined for the Boeing 777. It was found that this additional weight was less than 0.5% of the maximum take-off weight. This percentage can even be made smaller, depending on deliberate careful choice of materials. Also, this total additional weight can be balanced by reducing the design pay load while ensuring that the structural efficiency of the aircraft is not altered.

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