DECREASE IN GROUND-RUN DISTANCE OF AIRPLANES BY APPLYING ELECTRICALLY DRIVEN WHEELS

Hiroshi Kobayashi*, Akira Nishizawa*
*Japan Aerospace Exploration Agency

Keywords: STOL, electric motor, driving wheel

Abstract

A new takeoff method for small airplanes that employs electrically driven landing gear is proposed. Experiments using a model airplane driven by electrically powered wheels showed that the ground-run distance is decreased by half by using a combination of powered wheels and propeller without an increase of energy consumption during the ground-roll. A study was also conducted of the trade-off between the ground-run distance and flight performance of a full-size propeller airplane assuming that the motors and controllers of an existing electric vehicle were used to power the landing gear.

1 Introduction

To improve the convenience of air transportation systems, Short Take-Off and Landing (STOL) is a beneficial characteristic for any size of airplane. Applying powered high-lift systems is an effective method for achieving this goal[1],[2],[3]. However, such systems usually require airplane wings to be equipped with specially designed aerodynamic powered devices to achieve sufficient lift.

We propose a new method to decrease ground-run distance using landing gear driven by electric motors to augment the thrust of the engines. This system can be easily added to existing airplanes without changing aerodynamic designs.

In comparison with internal combustion engines, electric motors are generally very efficient and operate without producing exhaust gas or intense noise. Although past electric motor systems had the disadvantage of a small power-to-weight ratio, recent improvement of permanent magnet characteristics and breakthroughs in battery technology enable us to apply light and powerful electric motor systems[4] to airplanes.

The idea of using electrically driven landing gear to cut fuel consumption and decrease noise during taxiing is not new. Methods to drive landing gear by electric motors were demonstrated in the 1970s[5] and have been studied in recent years[6],[7],[8]. The present study is different from these because it considers not only taxiing but also ground-run.

In this study, the effectiveness of an electrically driven wheels system (EDWS) is demonstrated experimentally using a scale model. Also, the equations predicting ground-run distance when employing an EDWS are derived; these reveal the relationship between ground-run distance and the design parameters of an EDWS. Furthermore the feasibility of an EDWS is discussed on the assumption that existing electric motor systems are applied to a small propeller airplane for general aviation.

2 Experimental Setup and Conditions

2.1 Model

Figure 1 shows a 19% scale model of Cessna Skylane 182, which was used for the preliminary wind tunnel tests and the ground-run tests. The EDWS of the model was installed to the rear wheels because the normal force acting on the front wheel is so small that not enough thrust is obtained if the front wheel is driven.
When an EDWS is used in ground roll, a large pitch-up moment acts on the model because the thrust of the EDWS acts on a point below the center of gravity. Therefore, the rear-wheel drive has the disadvantage that the pitch-up motion causes the tail to contact with runway. To prevent such unfavorable motion an additional wheel was installed aft of the center of gravity.

The EDWS of the model is removable to enable the comparison of ground-run distances between different configurations (with or without the EDWS). Table 1 shows the specifications of the model in each configuration.

### Table 1 Specifications of the scale model

<table>
<thead>
<tr>
<th>Model configuration</th>
<th>Without EDWS</th>
<th>With EDWS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length (m)</td>
<td>1.64</td>
<td>2.06</td>
</tr>
<tr>
<td>Span (m)</td>
<td>2.06</td>
<td>2.06</td>
</tr>
<tr>
<td>Wing area (m²)</td>
<td>0.587</td>
<td>0.58</td>
</tr>
<tr>
<td>C_L</td>
<td>0.58</td>
<td>0.58</td>
</tr>
<tr>
<td>C_D</td>
<td>0.048</td>
<td>0.048</td>
</tr>
<tr>
<td>Mass (kg)</td>
<td>6.77</td>
<td>7.85</td>
</tr>
<tr>
<td>( V_{TO} ) (m/s)</td>
<td>13.0</td>
<td>14.0</td>
</tr>
<tr>
<td>Electric motor for EDWS</td>
<td>ModelMotors AXI2826/12 (Kv=760 rpm/V), 0.181kg</td>
<td></td>
</tr>
<tr>
<td>Battery for EDWS</td>
<td>Li-Po 5s (18.5V in nominal terms)</td>
<td></td>
</tr>
<tr>
<td>Wheel</td>
<td>Dia: 88mm, Width: 40mm</td>
<td></td>
</tr>
<tr>
<td>Gear ratio G</td>
<td>3.3</td>
<td></td>
</tr>
<tr>
<td>Propeller</td>
<td>Dia: 18 inch, Pitch: 12 inch</td>
<td></td>
</tr>
<tr>
<td>Electric motor for propeller</td>
<td>ModelMotors AXI3530/24 (0.652kg)</td>
<td></td>
</tr>
<tr>
<td>Battery for propeller</td>
<td>Li-Po 7s (25.9V in nominal terms)</td>
<td></td>
</tr>
</tbody>
</table>

Takeoff velocity \( V_{TO} \) is defined by multiplying the stall speed of the model by 1.2 in this study. The stall speed of the model is calculated using the maximum lift coefficient \( C_{L_{\text{max}}} = 1.59 \) found from preliminary wind tunnel tests [9]. Without the EDWS, the mass of the model is \( m = 6.77 \) kg and \( V_{TO} = 13.0 \) m/s. On the other hand, with the EDWS, \( m = 7.85 \) kg and \( V_{TO} \) increases to 14.0 m/s.

The propeller and wheels of the model are independently driven by brushless motors powered by lithium-polymer batteries. Each motor’s output is controlled by a motor controller receiving pulse-width modulated signals from a radio control transmitter and receiver set.

In the model, some sensors are installed to monitor the condition of the model and energy consumption. Outputs from the sensors are sampled at 100Hz and logged by a 12-bit data logger mounted on the model.

### 2.2 Experimental Conditions

The ground-run tests were conducted on a dry asphalt runway with three ground-run methods. Descriptions of these methods, labeled (a), (b) and (c), are given in Table 2.

### Table 2 Ground-run methods

<table>
<thead>
<tr>
<th>Method</th>
<th>(a)</th>
<th>(b)</th>
<th>(c)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model configuration</td>
<td>Without EDWS</td>
<td>With EDWS</td>
<td></td>
</tr>
<tr>
<td>Propeller thrust</td>
<td>Applied</td>
<td>None</td>
<td>Applied</td>
</tr>
<tr>
<td>Wheel thrust</td>
<td>None</td>
<td>Applied</td>
<td>Applied</td>
</tr>
<tr>
<td>Starting procedure</td>
<td>1) Hold the model and raise the propeller revolution to maximum. 2) Release the model.</td>
<td>1) Rapidly increase the EDWS power from zero to maximum.</td>
<td>1) Hold the model and raise the propeller revolution to maximum. 2) Release the model 3) Rapidly increase the EDWS power from zero to maximum</td>
</tr>
</tbody>
</table>

For each method, the velocity was increased from zero to \( V_{TO} \) during one run. Ground-run distance \( L_0 \) is defined as the distance from the starting position to the position where the velocity reaches \( V_{TO} \). Each \( L_0 \) is normalized by the value of \( L_0a \) for method (a), \( L_{0a} \).
3 Analytical Methods and Validation

3.1 Model for Friction between Runway and Tires

The thrust of the EDWS, $T_w$, is generated by friction between the runway and tires. Thus, the maximum value of $T_w$ is given by

$$T_{\text{wmax}} = W \mu$$

where $\mu$ is the coefficient of static friction between the runway and tires and $W$ is the normal force acting on the runway. It is known that $\mu$ is a function of the slip ratio

$$\lambda = \frac{r \omega - V}{r \omega}$$

where $r$ is radius of the wheels and $\omega$ is the rotational speed of the tires. Based on the mathematical model proposed by Pacejka et al.\[10\], $\mu(\lambda)$ is assumed to be

$$\mu = \mu_{\text{max}} \sin[1.65 \arctan(0.165 - \epsilon(0.165 - \arctan(0.165)))]$$

where $\mu_{\text{max}}$, $\beta$ and $\epsilon$ are constants determined by runway condition and the materials and shape of the tires. Preliminary ground-run tests\[9\] determined these constants to be $\mu_{\text{max}} = 0.53$, $\beta = 6$, and $\epsilon = 0.56$. Figure 2 shows $\mu(\lambda)$ as predicted by equation (3) and measured in the preliminary tests.

3.2 Torque Characteristics of DC Brushless Motors

In this study, a DC brushless motor is used as the power-train of the EDWS. When the output of the motor is at a maximum, the voltage of the power supply $E$ can be described by

$$E = \frac{N_m}{K_v} + IR$$

where $N_m$ is the rotational speed of the motor, $K_v$ is the back electromotive force coefficient, $R$ is the electrical resistance of the circuit including the motor and $I$ is the current in the circuit. Also, using the zero-torque current $I_0$, the torque of the motor $\tau$ can be described by

$$\tau = \frac{(I - I_0)}{K_v}$$

When the motor outputs maximum torque $\tau_{\text{max}}$, eliminating $I$ from equations (4) and (5) we have

$$E = \frac{N_m}{K_v} + R(K_v, \tau_{\text{max}} + I_0)$$

Furthermore, because $N_m$ is the product of $\omega$ and the gear ratio between the motor and tires $G$,

$$E = \frac{G \omega}{K_v} + R(K_v, \tau_{\text{max}} + I_0)$$

where $RI_0$ is usually negligibly small compared to the other terms.

On the other hand, the relationship of $T_w$ and $\tau$ is given by

$$T_w = \frac{G \tau}{r}$$

Thus, using equations (7) and (8), $T_{\text{wmax}}$ can also be written as

$$T_{\text{wmax}} = \frac{G}{K_v} \left[ E - \frac{G}{K_v} \rho \right] \frac{1}{Rr}$$

3.3 Transition of $T_{\text{wmax}}$

To minimize $L_0$, $T_w$ must be maximized consistently. As previously mentioned, $T_w$ is limited to the values described in equations (1)
and (9). Thus, \( T_{w\text{max}} \) is equal to the smaller of the two values given by equations (1) and (9).

When \( \lambda \) is controlled to be the constant \( \lambda_{\text{max}} \) which maximizes \( \mu \), we see from equation (2) that \( \omega \) is proportional to \( V \):

\[
\omega = \frac{V}{r(1 - \lambda_{\text{max}})} = c_4 V\quad \text{(10)}.
\]

Using equations (9) and (10), equations relating \( T_{w\text{max}} \) and \( V \) can be written:

\[
T_{w\text{max}} = \begin{cases} 
W\mu_{\text{max}} & (W\mu_{\text{max}} \leq -c_2\omega + c_1) \\
-c_4 c_4 V + c_1 & (W\mu_{\text{max}} > -c_4\omega + c_3) \end{cases}\quad \text{(11)},
\]

where setting \( c_2 \) and \( c_3 \) equal to \( T_{w\text{max}} \) in equation (11) gives the theoretical maximum value for a specified \( \mu_{\text{max}} \). To maintain \( \lambda \) equal to a specified value, current control methods\([11]\) used for electric vehicles (EVs) are expected to be effective.

### 3.4 Equation of Motion

When \( T_{w} \) is maximized, the equation of motion for the airplane equipped with the EDWS is

\[
m \left( \frac{dV}{dt} \right) = T_{p} - T_{w\text{max}} - D_{a} - D_{r}\quad \text{(12)},
\]

where \( T_{p} \) is thrust of the propeller, \( D_{a} \) is the aerodynamic drag and \( D_{r} \) is the rolling resistance between the runway and tires. From preliminary wind tunnel tests, the thrust coefficient \( C_{T} = T_{p}/(\rho N_{p}^{2} D_{p}) \) of the propeller used for the scale model can be assumed to be

\[
C_{T} = -C_{0}(V / N_{p} D_{p})^{2} + C_{1}\quad \text{(13)}.
\]

Then, \( W, D_{a} \) and \( D_{r} \) are described by

\[
W = mg - \frac{1}{2} \rho V^{2} SC_{L}\quad \text{(14)}
\]

\[
D_{a} = \frac{1}{2} \rho V^{2} SC_{D}\quad \text{(15)}
\]

\[
D_{r} = (mg - \frac{1}{2} \rho V^{2} SC_{L})\mu_{\text{coll}}\quad \text{(16)},
\]

where \( N_{p}, D_{p}, \rho, S \) and \( \mu_{\text{coll}} \) are the rotational speed of the propeller, the diameter of the propeller, air density, the wing area of the model and the coefficient of rolling friction, respectively. Using equations (13) – (16), an ordinary differential equation can be derived from equation (12) as follows.

\[
m \left( \frac{dV}{dt} \right) = -(C_{0} + C_{\mu})V^{2} + C_{1} + mg\mu_{\text{max}}(W\mu_{\text{max}} \leq -c_4\omega + c_1) - C_{2} V + C_{3} \quad (W\mu_{\text{max}} > -c_4\omega + c_3)\quad \text{(17)}.
\]

From this equation, general analytical solutions can be obtained:

\[
V(t) = \begin{cases} 
A_{i} \coth(C_{a1} t + C_{b1}) & (W\mu_{\text{max}} \leq -c_4\omega + c_1) \\
B_{i} \coth(C_{a1} t + C_{b1}) + B_{i} & (W\mu_{\text{max}} > -c_4\omega + c_1) \end{cases}\quad \text{(18)},
\]

where \( C_{a1} \) and \( C_{b1} \) are arbitrary constants of an initial-value problem.

\[
A_{i} = \left( \frac{C_{1} + \mu_{\text{max}}}{C_{0}} \right)^{\frac{1}{2}}, \quad C_{a0} = \frac{B_{i}}{m} \quad \text{and} \quad B_{i} = \frac{C_{1} + \mu_{\text{max}}}{2C_{0}}\quad \text{where} \quad C_{b0} = \frac{B_{i}}{m}.
\]

Thus, by integrating equation (18), the distance from the start position of the ground-run \( L(t) \) can be described by

\[
L(t) = \begin{cases} 
A_{i} \sinh(C_{a1} t + C_{b1}) + C_{a2} & (W\mu_{\text{max}} \leq -c_4\omega + c_1) \\
B_{i} \sinh(C_{a1} t + C_{b1}) + B_{i} + C_{b2} & (W\mu_{\text{max}} > -c_4\omega + c_1) \end{cases}\quad \text{(19)},
\]

where \( C_{a2} \) and \( C_{b2} \) are also arbitrary constants of an initial-value problem. The distance \( L(t) \) predicted using equation (19) is the theoretical minimum value because \( T_{w\text{max}} \) in equation (11) is the theoretical maximum value.

### 3.5 Validation

The values of \( L(t)/L_{0a} \) for methods (a) and (c) predicted using equation (19) are compared to the measured values in Fig. 3. The differences between the predicted and measured values are less than about 7% of the measured \( L_{0a} \), indicating the validity of the prediction method.
DECREASE IN GROUND-RUN DISTANCE OF AIRPLANES BY APPLYING ELECTRICALLY DRIVEN WHEELS

4 Results

4.1 Ground-run Distance

Figure 3 shows the ground-run distance \( L(t)/L_{0a} \) obtained by the three methods. By applying method (c), which couples the thrusts of the propeller and the EDWS, \( L_0/L_{0a} \) is decreased by one half compared to that of method (a) which uses only the propeller thrust. The results show the effectiveness of the ground-run method proposed in this study.

Figure 4 shows the relation between \( V/V_{TO} \) and acceleration \( a \) (normalized by the acceleration due to gravity \( g \)) during the ground-run. It is found that the accelerations using the EDWS (methods (b) and (c)) are much higher than that without the EDWS (method (a)).

Although \( a/g \) for method (b) is almost twice that of method (a) at \( V/V_{TO}<0.5 \), the ground-run distances are not so different (see Fig. 3). The reason why method (b) cannot decrease \( L_0/L_{0a} \) drastically is that it takes considerable time to accelerate the model when \( V/V_{TO} \) exceeds 0.95.

4.2 Efficiency

Figure 5 shows propulsion efficiency

\[
\eta_p = \frac{TV}{EI} \tag{20}
\]

As shown in Fig. 5, the value of \( \eta_p \) for method (b) is the highest at almost all \( V/V_{TO} \) and this feature of \( \eta_p \) becomes more prominent when \( V/V_{TO} \) is large. This fact indicates that EDWS has an advantage in terms of energy consumption not only for taxiing but also for ground-run.

4.3 Design Parameters

When designing an EDWS, various factors should be taken into consideration, including the selection of electric motors and batteries, and the structure of the landing gear including drive system. As described in equations (1), (9) and (14), when \( r, C_L, \) and \( \mu_{max} \) are known, the relationship between \( V \) and \( T_{w\ max} \) is governed by \( E, G/K_v \) and \( R \); here, \( R \) is the sum of electrical resistances of the motor coils, power lines and the motor controller. To simplify the following discussion, \( R \) is assumed to be constant. Thus, in the conceptual design phase, a combination of \( K_v, G \) and \( E \) for achieving the required \( L_0 \) must be determined.

Figure 6 shows \( L_0/L_{0a} \) for method (c) with various values of \( G/K_v \) and numbers of battery cells (1 cell: 3.7V) in series. As shown in Fig. 6, \( L_0/L_{0a} \) becomes smaller for higher \( E \). This is because, for high \( E, T_{w\ max} \) can be kept large for
large $\omega$ or large $V$ as described in equations (9) and (10).

Assuming that $C_{L_{\text{max}}}$ is proportional to $\delta$, $C_{L_{\text{max}}}$ is 1.93 at takeoff ($\delta = 20^\circ$) and the stall speed is 24.0m/s. Then, $V_{T0} = 1.2 \times 24.0 = 28.8$m/s. To simplify the following discussion, the aerodynamic coefficients and friction characteristics during ground-run are assumed to be $C_D = 0.0341$, $C_L = 0.0$, $\lambda_{\mu_{\text{max}}} = 0.1$ and $\mu_{\text{max}} = 1.05$. The friction coefficient assumed above is equivalent to that between ordinary bias tires and dry asphalt[14].

Considering recent improvements in performance, the motor systems used for EVs are supposed to be suitable for use in an EDWS. Table 4 shows the specifications of electric motor systems of typical EVs.

Generally, when size of the motor becomes large, the resistance of the motor coils $R_c$ tends to be large, becoming the dominant contribution to $R$. Thus, $R$ is assumed to be equal to $R_c$ and the resistance of the motor used for KAZ (0.5ohm) is adopted as $R_c$ in this section. Then, $K_v$ of the motor can be obtained from equation (4) as

$$K_v = \frac{N_{P_{\text{max}}}}{E_{\text{max}} - IR}$$

where $N_{P_{\text{max}}}$ is the rotational speed of the motor at maximum output and $E_{\text{max}}$ is the maximum voltage of the motor controller. Also, $I$ is estimated using the efficiency of the motor system $\eta_m$:

$$I = \frac{P_{\text{max}}}{E_{\text{max}} \eta_m}$$

where $P_{\text{max}}$ is the maximum output of the motor and $\eta_m$ is assumed to be 0.8.
Figure 7 shows the relationship between $L_0/L_{0a}$ and $G/K_v$ for a Cessna Skyhawk 172 equipped with an EDWS. In addition, a nominal ground-run distance of 288m is used as $L_{0a}$. As shown in Fig. 7, $L_0/L_{0a}$ decreased to 0.41 at $G/K_v \approx 7$. From Table 4, this value can be achieved using the motor in the KAZ with $G = 5.2$ which indicates that using an EDWS based on an existing motor system could drastically decrease the ground-run distance of small airplanes.

6 Effects on Flight Performance

Although an EDWS has the potential to decrease ground-run distance, the weight of an EDWS estimated as the sum of the weights of the motor $W_m$, the controller $W_c$ and battery $W_b$, is not usually light for small airplanes. In fact, the total of $W_m$ and $W_c$ for the KAZ is about 490N from Table 4. Using a recently developed lithium-ion battery with a high power-weight ratio (3.5kW/kg)[15], $W_b$ is about 590N. Therefore, the total weight of an EDWS is about 1080N. To equip an airplane with an EDWS, the fuel on board has to be cut to maintain the maximum takeoff weight. For a Cessna Skyhawk 172 with a fuel tank volume of 0.2m³, the total weight of fuel is calculated to be 1471.5N from specific weight of gasoline 0.71. Subtracting the weight of the EDWS from the fuel weight calculated above, the available fuel weight decreases to 391.5N. The range $R_a$ also decreases from a normal range of $R_{a0} = 1270km$ to 338km, assuming $R_a$ is proportional to fuel weight.

Figure 8 shows the relationship between $L_0/L_{0a}$ and $R_a/R_{a0}$ for various values of $E$ and $G/K_v$ or for different capacities of the supplied reciprocating engine. $L_0/L_{0a}$ and $R_a/R_{a0}$ become smaller for higher $E$. This is due to the increase of $W_b$ needed to obtain larger torque at high velocity. Furthermore, $L_0/L_{0a}$ and $R_a/R_{a0}$ are in trade-off relation with respect to the optimum design point ($G/K_{vopt}$ in Fig. 7) for each value of $E$. On the other hand, installing a larger reciprocating engine (increasing propeller thrust) can also decrease $L_0/L_{0a}$. However, the effect of the weight increase on the decrease of $R_a/R_{a0}$ is much greater than that of an EDWS. Fitting an EDWS can provide a larger $R_a/R_{a0}$ at $L_0/L_{0a} < 0.75$ than increasing the capacity of the reciprocating engine, indicating the advantage of an EDWS.

7 Summary

A new ground-run method using electrically driven wheels for the landing gear was proposed. The results of experimental and analytical investigation led to the following conclusions.
1) Concurrent operation of an EDWS and propeller can drastically decrease ground-run distance compared to the conventional takeoff method.
2) Fitting an EDWS improves propulsion efficiency during the ground-run.
3) Ground-run distance and range are in a trade-off relation and there is an optimum
design point in the case of an EDWS using a standard EV motor system.

4) Using an EDWS to decrease ground-run distance has the advantage over just increasing engine capacity of requiring a smaller sacrifice of range.

References


Copyright Statement

The authors confirm that they, and/or their company or organization, hold copyright on all of the original material included in this paper. The authors also confirm that they have obtained permission, from the copyright holder of any third party material included in this paper, to publish it as part of their paper. The authors confirm that they give permission, or have obtained permission from the copyright holder of this paper, for the publication and distribution of this paper as part of the ICAS2010 proceedings or as individual off-prints from the proceedings.